Recent Advances in DFB Lasers for Ultradense WDM Applications

Article *in* IEEE Journal of Selected Topics in Quantum Electronics · April 2004

DOI: 10.1109/JSTQE.2004.826576 · Source: IEEE Xplore

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Recent Advances in DFB Lasers for Ultradense WDM Applications

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Invited Paper

***Abstract*—State-of-the-art distributed feedback (DFB) laser modules integrated with a wavelength monitor are presented that provide excellent wavelength stability. By adopting unique and compact configuration, wavelength deviations of as small as a few picometers have been achieved. The laser modules are improved also in the scope of high power, high reliability, and wavelength tunability. Reliability test results of the DFB laser diodes and modules confirm a sufficiently long lifetime of more than 25 years and a small wavelength drift of less than ± 3 pm. The developed laser modules are fully applicable to ultradense wavelength-division multiplexing applications with the current narrowest channel spacing of 25 GHz.**

***Index Terms*—Distributed feedback lasers, laser stability, semiconductor device packaging, semiconductor lasers, wavelength-division multiplexing.**

I. Introduction

In order to support the rapid growth of Internet, long-haul fiber-optic transmission capacity has been expanded intensively by means of developing dense wavelength-division multiplexing (DWDM) technology. There are three approaches to enhance WDM transmission capacity: multiplying channel counts by narrowing channel spacing down to 50 or 25 GHz, increasing bit rates up to 40 Gb/s, and using a wavelength band of L- or S-band in addition to C-band.

The first approach has an advantage that it can utilize the existing mature technologies of 10-Gb/s $LiNbO_3$ modulators and C-band optical components like erbium-doped fiber amplifiers, continuous-wave (CW) distributed feedback (DFB) lasers, and other passive components. To realize such DWDM systems with the very narrow channel spacing, however, new requirements have emerged regarding wavelength properties of transmitters, such as accuracy on an ITU-T grid, stability against environmental changes, and lineup over entire transmission band. As channel spacing gets narrower, acceptable variation of the laser wavelength becomes more severe. Furthermore, it has to be maintained throughout lifespan of more than 20 years. Allowable frequency (or wavelength) deviations in 10-Gb/s applications recommended by ITU-T [1] are summarized in Table I for typical channel spacings.

TABLE I
ALLOWABLE FREQUENCY DEVIATIONS FOR TYPICAL CHANNEL SPACINGS (10-Gb/s APPLICATIONS)

Channel spacing (GHz)	100	50	25
Allowable frequency deviation (GHz)	20	7.5	1.25
Allowable wavelength deviation (pm)	~160	~60	~10

Since the conventional way of controlling laser modules cannot meet the stringent requirements, a new technique that provides a higher degree of wavelength stability was demanded, which is so-called wavelength locking or wavelength monitoring [2]–[6].

We developed several types of DFB laser modules integrated with the wavelength monitor as well as control technique to achieve better wavelength stability. Besides high wavelength stability, there are continual demands for upgraded characteristics, such as high output power, low intensity and phase noises, low power consumption, and high reliability. Those points are also taken into account in our design. The developed DFB laser modules are fully adaptable to the latest ultradense WDM applications.

In this paper, first, basic structures of a DFB laser diode and a laser module are described in Section II. In Section III, concepts and performances of several types of DFB laser modules with integrated wavelength monitor function are discussed. Reliability properties of the laser diodes and modules are presented in Section IV. Section V summarizes recent advances in DFB laser modules integrated with the wavelength monitor developed for ultradense WDM applications.

II. Basic Structures of Laser Diode and Module

A. Laser Diode Structure

Major laser diode structures used for recent CW DFB lasers are buried-hetero (BH) structure and ridge waveguide structure [7]–[17]. We employed the BH structure because it provides

Manuscript received October 24, 2003; revised February 12, 2004.

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Digital Object Identifier 10.1109/JSTQE.2004.826576

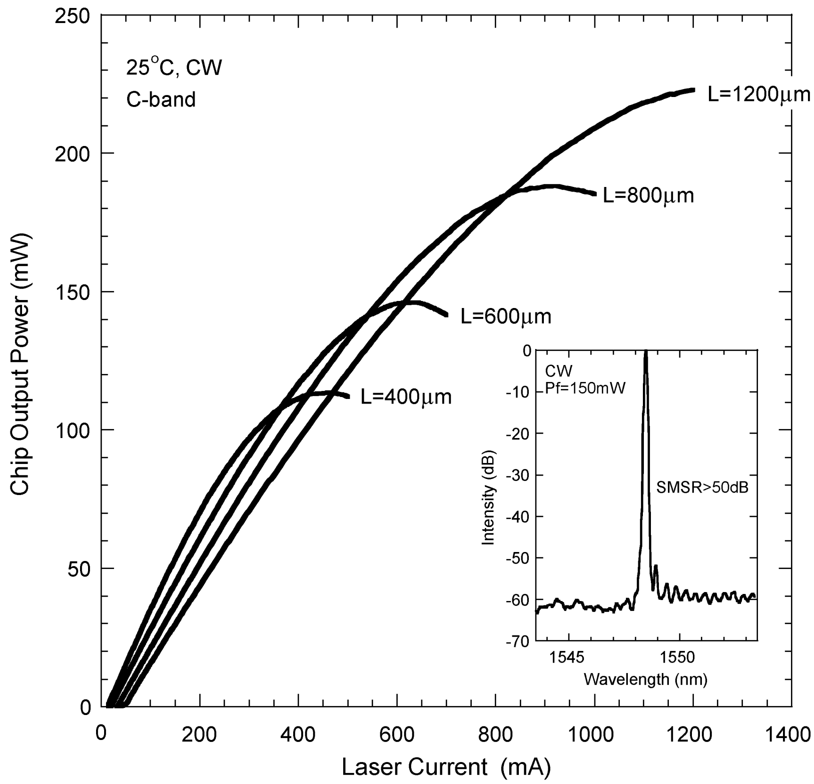

Fig. 1. L-I characteristics of the C-band DFB laser diodes with different cavity lengths of 400, 600, 800, and 1200 μm. The inset shows spectrum from a packaged 800-μm-long DFB laser at a fiber coupled power of 150 mW.

better current confinement, low waveguide loss, and circular and stable beam shape. These features enable us to make high-power laser diode modules (LDM) with low power consumption.

The active layer comprised InGaAsP strain-compensated six multiquantum wells and multistepped separate confinement hetero structures. A corrugation pattern was formed above the active layer. Our solution of the upper grating using both electron beam lithography and dry-etching techniques are thought to be effective for making DWDM DFB laser diodes with different wavelengths on one wafer. Mesa shape with 2-μm width was formed and buried with p- and n-type InP current blocking layers. All layers were grown by metal organic chemical vapor deposition.

The Bragg wavelength of a DFB laser diode $(\lambda_{\rm Bragg})$ is given by the simple equation $\lambda_{\rm Bragg} = 2\ {\rm n_{eff}}\Lambda$, where ${\rm n_{eff}}$ is the effective refractive index and Λ is the grating pitch. In order to obtain a desired wavelength accurately, both parameters have to be well controlled.

The grating pitch is fixed in the grating fabrication process, where electron beam lithography, holographic exposure, or phase mask techniques are usually used. On the other hand, the effective refractive index is determined by the refractive index profile of the laser waveguide structure and can be affected by many factors. Therefore, the composition and thickness of each layer should be accurately controlled in the growth process. In the fabrication process, mesa width in the BH structure or remaining thickness of upper cladding layer in the ridge waveguide structure must be formed with utmost care. Strictly speaking, the DFB laser wavelength does not perfectly coincide with the Bragg wavelength because of stopband and uncertainty of grating phases at the facets. Moreover, the effective refractive index can vary depending on driving conditions such as laser temperature or laser current. Due to the above reasons, temperature control is often used to fine-tune the DFB wavelength precisely to an ITU-T grid.

Cavity length (L) of the DFB laser was chosen depending on a required output power. Coupling coefficient (κ) of the grating was determined so that the product of κ and L gave around unity, where high slope efficiency and high single-longitudinal-mode yield can be obtained simultaneously. Laser front and rear facets were coated with antireflection and high-reflection films, respectively. The DFB laser diode was bonded on a submount in junction-down configuration to reduce thermal resistance. The small thermal resistance suppresses heating of the active layer due to current injection; thus it is very effective for high output power and small wavelength drift, which will be mentioned later. Output power characteristics of the DFB laser diodes with different cavity lengths are shown in Fig. 1. Single mode output power of over 200 mW as well as a large side mode suppression ratio (SMSR) of about 50 dB has been achieved in C-band [8]. High output power of over 100 mW is also realized in L-band DFB lasers at 1625-nm wavelength [16], [17]. The full-width at half-maximum of the far-field pattern is typically 20° in horizontal direction and 24° in vertical direction, respectively.

B. Laser Module Structure

The DFB laser chip on the submount was assembled into an industry standard 14-pin butterfly package with a standard single mode fiber or a polarization maintaining fiber (PMF) pigtail. The PMF is required in the case of connecting an external $LiNbO_3$ modulator, which usually has polarization-dependent characteristics. The package normally includes a thermoelectric cooler (TEC), a thermistor, a power monitor photodiode, and an optical isolator. In order to achieve better coupling efficiency from the laser diode to the fiber pigtail, we adopted a two-lens configuration. YAG welding and soldering techniques used in the module assembly contribute to high alignment accuracy and long-term reliability. Owing to these, high coupling efficiency of more than 80% has been obtained. Spectral linewidth and relative intensity noise (RIN) of the DFB laser module are low enough for practical use, and are typically a few megahertz and -160 dB/Hz, respectively.

III. Designs and Performances of DFB Laser Modules With Wavelength Monitor Function

A. Regular DFB Laser Module

Before going into discussion about the wavelength locking, we start with a regular DFB laser module that does not have the wavelength monitor function and describe several factors that affect stability of the lasing wavelength.

Generally, DFB laser modules as WDM sources are operated in an automatic power control (APC) mode for practical application. As a laser diode deteriorates with age, laser operating current increases gradually to keep a constant output power. The increase of the operating current generates more heat in the active layer and causes positive wavelength shift. The wavelength (λ) shift due to the laser injection current $(\mathrm{I_f})$ can be expressed as

$$\begin{aligned}\lambda(\mathrm{I_f}) &= \lambda_0 + \frac{\partial\lambda}{\partial \mathrm{T}}\mathrm{R_{th}}(\mathrm{I_f V_f} - \mathrm{P_o})\\ &\cong \lambda_0 + \frac{\partial\lambda}{\partial \mathrm{T}}\mathrm{R_{th}}\left\{\mathrm{I_f}(\mathrm{V_{th}} + \mathrm{RI_f}) - \mathrm{P_o}\right\}\end{aligned} \tag{1}$$

where λ_0 is the virtual wavelength under no current injection, $\partial\lambda/\partial\mathrm{T}$ is the wavelength temperature coefficient (typically 100 pm/°C), $\mathrm{R_{th}}$ is the thermal resistance, $\mathrm{V_f}$ and $\mathrm{V_{th}}$ are the forward and threshold voltages of the laser diode, R is the differential resistance, and $\mathrm{P_o}$ is the chip output power. As one can see from (1), the wavelength increases in proportional to the square of laser current. This expression explains well the measured wavelength shifts of the DFB laser modules as a function of the laser current shown in Fig. 2. In order to reduce the wavelength shift, low operating current, small thermal resistance, and small differential resistance are effective. Since a longer cavity is advantageous to reduce the thermal and differential resistances, it leads to smaller wavelength shift.

Using these wavelength-current curves, one can roughly estimate how large wavelength shift will occur along with the increase of operating current. Suppose, for instance, the operating current is 100 mA for $L = 400$ μm at the beginning of life, where wavelength current coefficient is 5 pm/mA (derivative of the wavelength-current curve). Assuming that the operating current increases to 120 by 20 mA at the end of life (20% increase), the approximate wavelength shift is calculated as 5 pm/mA $\times$ 20 mA $=$ 100 pm. More precise wavelength shift can be estimated using (1) by calculating a change of $(\mathrm{I_f V_f} - \mathrm{P_o})$, where both current increase and power decrease after degradation are taken into account.

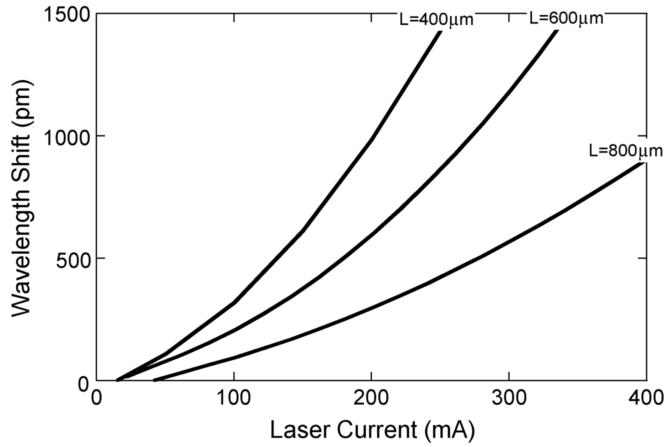

Fig. 2. Wavelength shift as a function of laser current measured for packaged DFB lasers with different cavity lengths.

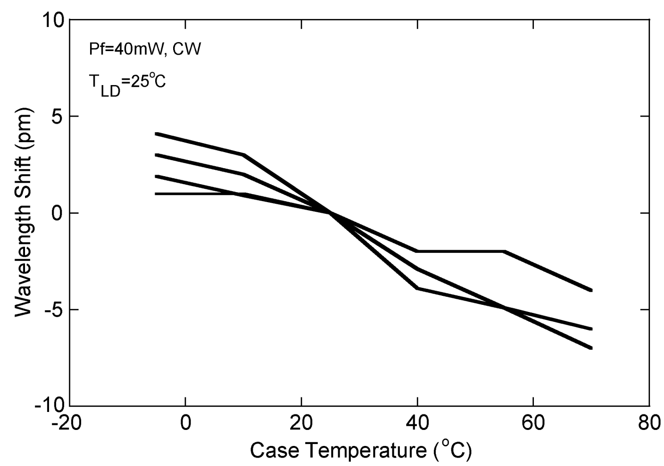

Fig. 3. Wavelength shift as a function of case temperature in the regular DFB laser modules. Power monitor photocurrent is kept constant.

It is well known that the wavelength of the DFB laser is sensitive to laser temperature with a coefficient of around 100 pm/°C. This implies that fine temperature control on the order of 0.01 °C is necessary to attain negligibly small wavelength fluctuation of less than 1 pm. Even if the temperature of the DFB laser diode is well stabilized using an automatic temperature control by monitoring thermistor resistance, change of package case temperature (Tc) may cause wavelength shift because it can affect the thermistor temperature thorough thermal radiation. The amount of the wavelength shift due to the thermal radiation depends on geometric and thermal configurations among the laser diode, the thermistor, and the package lid. Fig. 3 shows measured relations between the wavelength shift and the case temperature in the regular DFB laser modules. When the case temperature rises, the thermistor is heated and feedback circuit tries to keep the constant thermistor temperature. As a result, the laser diode temperature becomes slightly lower than the thermistor temperature, thus causing the negative wavelength shift. The amount of wavelength shift

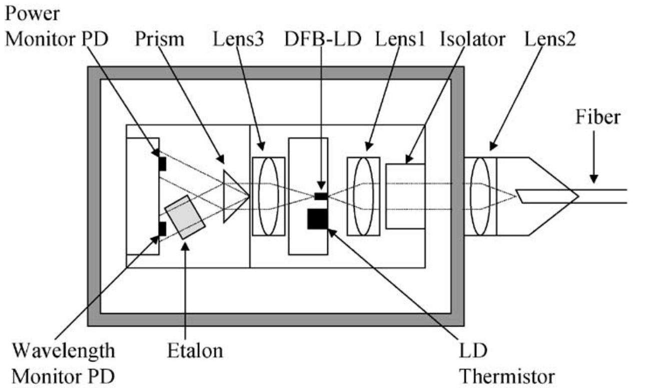

Fig. 4. Schematic of the DFB laser module with wavelength monitor function integrated in the standard 14-pin butterfly package.

over the case temperature from -5 to 70 °C is approximately less than ± 10 pm.

Compared to the allowable wavelength deviations in Table I, the wavelength shifts due to the change of the laser current (100 pm) and the case temperature (± 10 pm) in the regular DFB laser module are acceptable for 100-GHz channel spacing but not acceptable for 50 GHz. Therefore, the wavelength locking is essential for the spacing of 50 GHz or less.

B. Fixed Wavelength DFB Laser Module for 50-GHz Channel Spacing

To achieve better wavelength stability, the wavelength monitor function was embedded in the butterfly package of the same size [6]. Fig. 4 is a schematic of the wavelength monitor integrated DFB laser module, which includes a Fabry–Perot etalon and a second photodiode to provide a wavelength discrimination signal. Among several techniques reported on the wavelength monitor function [2]–[6], we decided to use the Fabry–Perot etalon because of its compactness and periodic property of transmission factor. These features are advantageous in terms of integration into a standard-size package and wavelength locking at multiple ITU-T grids.

A laser beam from the front facet of the DFB laser diode is collimated by lens1, passes through the optical isolator, and is coupled into the fiber by lens2, which is common configuration to the regular DFB laser module. In order to produce the wavelength discrimination signal as well as the power monitor signal, a laser beam from the rear facet is collimated by lens3 and split into two beams by the prism. One beam is directly coupled into the power monitor photodiode and the other beam goes through the etalon and is received at the wavelength monitor photodiode. Since the etalon has transmission factor that changes periodically with respect to wavelength, wavelength shift can be detected by monitoring the change of photocurrent from the wavelength monitor photodiode, thereby enabling wavelength stabilization with the use of an electric feedback circuit.

The wavelength discrimination curve measured from the laser module with a 50-GHz etalon is plotted in Fig. 5, where the laser temperature was changed from 20 to 35 °C. The ITU-T grids shown as closed circles on the wavelength discrimination curve are located near the midpoints of the slopes, where sensitive detection of wavelength change is possible.

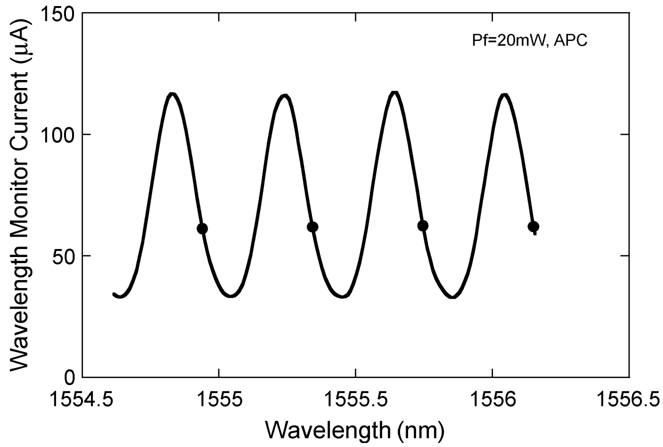

Fig. 5. Wavelength discrimination curve of the fixed wavelength DFB laser module for 50-GHz channel spacing. ITU-T grids are plotted as closed circles.

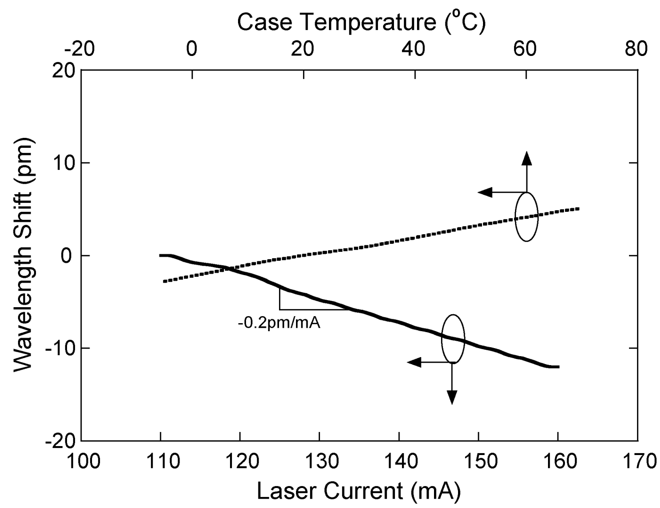

Fig. 6. Wavelength shifts as a function of laser current and case temperature in the fixed wavelength DFB laser module for 50-GHz channel spacing.

To investigate the wavelength stability of the laser module, we measured wavelength shifts as a function of the laser current and the case temperature (Fig. 6). As seen in Fig. 6, the lasing wavelength decreases as the laser current increases. The wavelength current coefficient is -0.2 pm/mA, which is much smaller than that of the regular DFB laser module. Assuming a current increase of 20 mA, a small wavelength shift of -4 pm is expected.

This negative coefficient is explained as follows. As the laser current increases, the active layer is heated and lasing wavelength goes longer. This wavelength shift is detected by the wavelength monitor and adjusted to maintain the constant wavelength by reducing the laser temperature. Simultaneously, the temperature of the etalon decreases, which is placed on the same base plate as the laser diode. As a result, the wavelength moves slightly shorter because the wavelength temperature coefficient of the etalon is positive.

The wavelength shift due to the case temperature change from -5 to 70 °C is also improved to be only ± 5 pm. As the case temperature becomes higher, the etalon is heated due to the thermal radiation. This brings a small positive shift of the wavelength discrimination curve, thus causing the slight positive shift of the lasing wavelength.

C. Fixed Wavelength DFB Laser Module for 25-GHz Channel Spacing

Since the cavity of an etalon for 25-GHz channel spacing is approximately twice as long as that for 50 GHz, it is very difficult, in general, to integrate the 25-GHz etalon into the standard 14-pin butterfly package. However, we realized it by compact optics arrangement using the prism as a beam splitter instead of a half-mirror [18]–[21]. With the use of the prism, the two photodiodes can be mounted on the same submount. This brings benefits of not only open space for the long-cavity 25-GHz etalon but also a reduced number of parts and simplified assembly process.

As mentioned above, the allowable wavelength variation for 25-GHz spacing applications is as tight as less than 10 pm. Although the wavelength stability is much improved by introducing the wavelength locking function as described in Section III-B, the resultant wavelength variation is applicable for 50-GHz channel spacing applications but not sufficiently small for 25-GHz spacing. In this section, we discuss further improvement of the wavelength stability for 25-GHz applications.

The wavelength variations in Fig. 6 are mainly due to two reasons. One is that the etalon temperature cannot be measured accurately. The second is that the wavelength temperature coefficient of the etalon is not considered in the generation of the feedback signal. To solve these problems, we attach an additional thermistor for monitoring the etalon temperature and introduce a new feedback algorism that achieves a higher degree of wavelength stability [18]. The features of the new feedback algorism utilizing thermal compensation are explained below.

With the added etalon thermistor, the drift of the wavelength discrimination curve as a function of the etalon temperature (to be precise, the etalon thermistor resistance) was measured in advance over the case temperature range from -5 to 70 °C. From the result, one can obtain wavelength monitor photocurrent values to maintain a specified lasing wavelength at each case temperature, as shown in Fig. 7.

The wavelength monitor photocurrent decreases linearly as the etalon thermistor resistance increases with a gradient of $-26.3\ \mu\mathrm{A/k}\Omega$. By monitoring the change of the actual etalon temperature from a reference temperature (e.g., 25 °C), locking target value of the wavelength monitor photocurrent was varied using the gradient.

By using this feedback technique, wavelength drift with a laser current change from 80 to 120 mA was suppressed to be less than 0.5 pm, as shown in Fig. 8. Wavelength variation over the case temperature range was found to be as small as ± 0.25 pm. These small wavelength deviations meet the requirement for the 25-GHz spacing WDM applications in Table I, hence indicating that this laser module combined with the thermal compensation feedback algorism is promising.

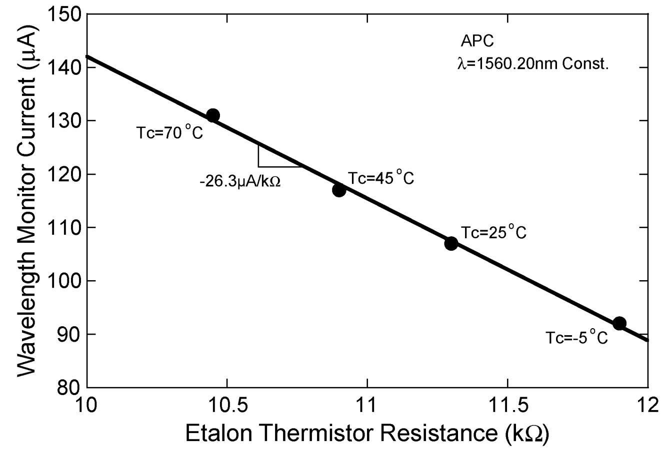

Fig. 7. Wavelength monitor photocurrent as a function of etalon thermistor resistance. The lasing wavelength is kept constant over the case temperature from -5 to 70 °C.

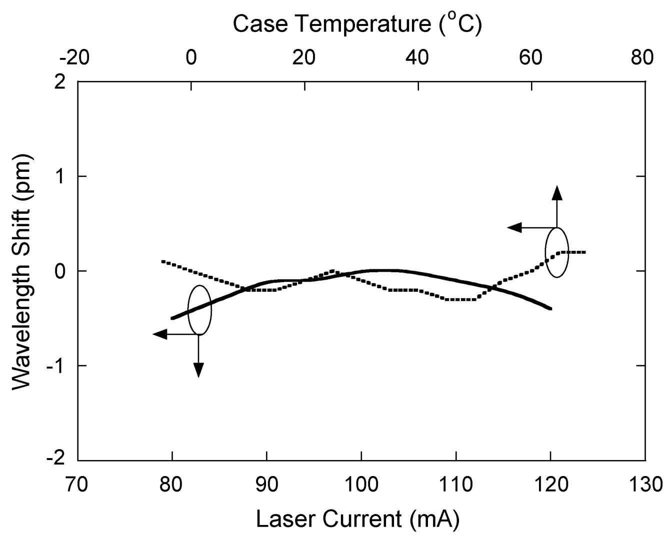

Fig. 8. Wavelength shift as a function of laser current and case temperature in the fixed wavelength DFB laser module for 25-GHz channel spacing. Case temperature was set at 25 °C in the measurement against laser current. Power monitor current was kept constant in the measurement against case temperature.

D. Thermally Tunable DFB Laser Module for 25 GHz × 20 ch

As DWDM technologies progress, channel counts of large systems can be more then 100. In such systems, repair and maintenance become a significant issue, but it is not a cost-effective way to have a great number of spare DFB laser modules for each ITU-T grid. Against this background, wavelength tunability has been strongly desired to cover multiple ITU-T grids by one laser module.

Among several approaches to enhance the tunability of the laser, thermal tuning is an unspectacular but very reliable method, and therefore it is widely used. In the thermal tuning, laser temperature is varied over a few tens of degrees, thereby achieving a wavelength tunable range of 2∼4 nm. Although the thermal tunability can be improved by expanding the temperature range of the DFB laser, there are factors limiting both the lower and upper side of the laser temperature range. First, when the laser temperature goes lower, the difference

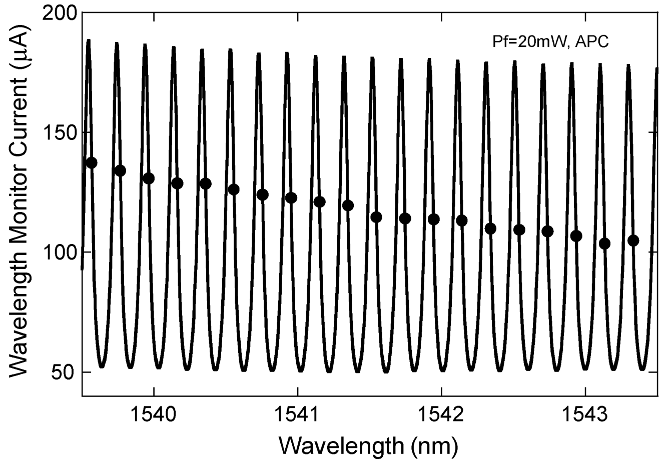

Fig. 9. Wavelength discrimination curve of the thermally tunable DFB laser module for 25-GHz channel spacing.

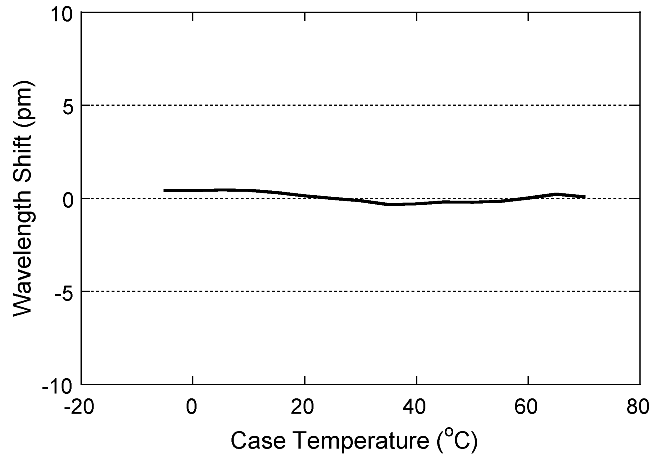

Fig. 11. Wavelength shift as a function of case temperature in the thermally tunable DFB laser module for 25-GHz channel spacing.

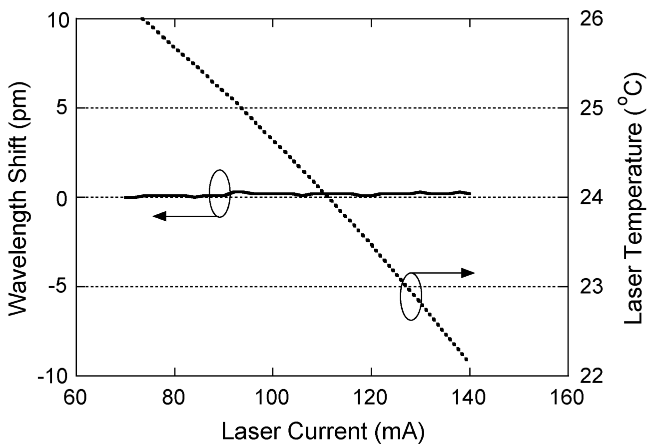

Fig. 10. Wavelength shift as a function of laser current in the thermally tunable DFB laser module for 25-GHz channel spacing. Laser temperature is also plotted with dashed line that decreases as laser current increases.

between the laser temperature and the specified maximum case temperature becomes large and the power consumption of the TEC drastically begins to increase. On the other hand, as the laser temperature rises, the performance and reliability of the DFB laser diode degrade. Thus, the lower and upper temperature limits should be determined through a careful consideration of this tradeoff as well as moderate margin to ensure reliability over lifespan.

To support a wide range of laser operating temperature, we employed a 2-TEC configuration that can control temperatures of the laser and the etalon independently [19]–[21]. Owing to this, accurate control of the etalon temperature and reduction of the power consumption are possible.

The wavelength tunability over 20 channels with 25-GHz spacing (approximately 4 nm) was demonstrated by changing the laser temperature from 5 to 45 °C, while the etalon temperature was kept constant at 30 °C [21]. As shown in Fig. 9, all of the 20 ITU-T grid frequencies are located near the middle points of the slopes on the wavelength discrimination curve. We obtained an excellent wavelength stability of less than 0.2 pm against the laser current change from 80 to 140 mA (Fig. 10). Fig. 10 also shows the measured laser temperature that is adjusted to compensate the heating due to the current injection. Wavelength drift over the case temperature from −5 to 70 °C was as small as 1 pm (Fig. 11). These small wavelength deviations are owing to the independent temperature control by the 2-TEC configuration.

Even at a high laser operating temperature of 45 °C, the laser module exhibited a very high PMF coupled power of more than 60 mW together with a very low operating current of less than 175 mA for 40 mW. This high-efficiency laser diode and the 2-TEC configuration contribute to the very low total power consumption of less than 4 W for the two TECs.

IV. Reliability of Laser Diodes and Modules

There are many kinds of reliability tests that must be carried out to qualify a laser module as a WDM source, whose lifetime is demanded to be more than 20 or 25 years in general. The commonly required test items are described in Telcordia GR-468-CORE [22]. We performed those reliability tests for both laser diodes and laser modules [23]. Since long-term wavelength stability is the main concern, here we focus on the test results that are closely related to the wavelength stability.

A. Chip Reliability

Increase of the laser operating current due to degradation of the laser diode is a dominant factor to affect the wavelength shift of the regular DFB laser without the wavelength monitor. Even with the wavelength monitor, when the laser diode and the etalon are on the same base plate, the wavelength can be affected by the current increase. In addition, the increased laser current shortens the life of the laser diode and raises the TEC power consumption. From these points of view, the smaller current increase is the better. To investigate the reliability of the DFB laser diodes, accelerated aging tests over 5000 h were carried out at different temperatures up to 70 °C and under APC operation at a corresponding fiber output power of 20 mW. Lifetime was calculated using linear extrapolation and defining end-of-life criteria of 20% increase in operating current from its initial value. It was found that the estimated median lifetime of our DFB laser

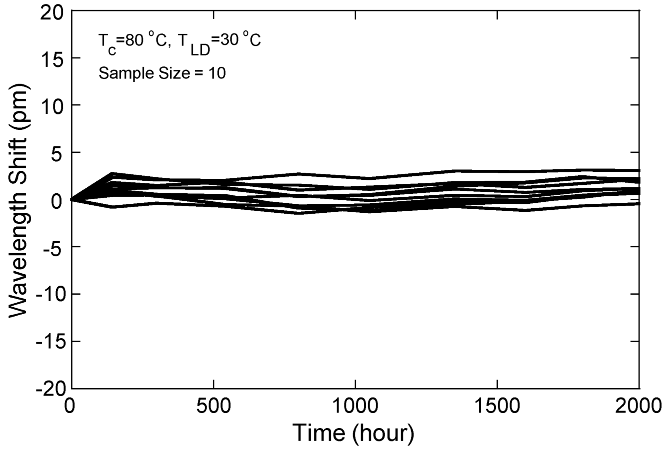

Fig. 12. Wavelength shift as a function of time in the accelerated aging test for the DFB laser module integrated with the wavelength monitor.

diodes is far more than 25 years, even at a high laser temperature of 45 °C. The activation energy was 0.69 eV. The increase of the laser current after 25 years is estimated to be only a few percent. This high reliability enables our DFB lasers to be used up to the high temperature of 45 °C for the thermally tunable purpose.

B. Module Reliability

Regarding the packaged modules, we performed systematic reliability tests of mechanical shock, vibration, accelerated aging, high and low temperature storage, and temperature cycling according to [22]. During the tests, laser current, lasing wavelength, and fiber-coupled power were measured for each module operating at a constant power monitor photocurrent. By checking the changes of the laser current and the lasing wavelength, we investigated stability of the optics system on the backside of the DFB laser diode. On the other hand, stability of the foreside optical coupling can be diagnosed by the change of the fiber-coupled power.

Fig. 12 shows the results of the accelerated aging test with respect to the laser modules described in Section III-B, where the case temperature was kept at 80 °C, while the laser temperature was maintained at 30 °C. Although this is one of the most severe module reliability tests, a small wavelength drift of ±3 pm has been obtained throughout 2000 h. All the other tests were also passed with sufficiently small wavelength deviations.

V. Conclusion

We have developed three types of DFB laser modules integrated with the wavelength monitor to realize the high degree of wavelength stability required for ultradense WDM applications. The developed laser modules showed the excellent wavelength stability against the changes of the operating conditions and through the accelerated aging tests. The results are summarized in Table II. Additionally, improved performances were presented such as output power of more than 40 mW, SMSR of more than 50 dB, narrow spectral linewidth, low RIN, tunability over 20 ITU-T grids, and very high reliability.

These DFB laser modules are fully applicable to the practical DWDM systems with 50- and 25-GHz channel spacing.

TABLE II
Summary of Wavelength Shifts ($\Delta\lambda$) Due to a Change of Laser Current (ΔIf) and Case Temperature (ΔTc) Evaluated for the Developed DFB Laser Modules

Module feature, Etalon type	TEC, Thermistor (QTM)	Δλ due to ΔIf [pm]	Δλ due to ΔTc [pm]	Applicable channel spacing [GHz]
Regular w/o etalon	1-TEC, 1-QTM	100	±10	100
Fixed, 50GHz	1-TEC, 1-QTM	-4	±5	50
Fixed, 25GHz with thermal-compensation	1-TEC, 2-QTM	±0.5	±0.25	25
Tunable, 25GHz	2-TEC, 2-QTM	±0.2	±1	25

Acknowledgment

The authors would like to thank K. Hiraiwa, K. Maruyama, N. Yamanaka, and S. Koizumi for laser fabrication. The authors also acknowledge valuable technical support in assembly and evaluation from S. Yoshimi and T. Satoh.

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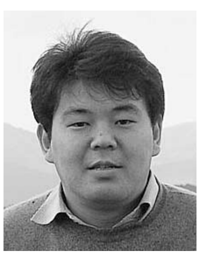

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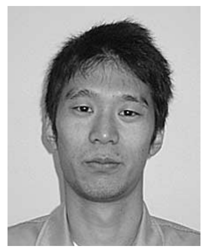

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