Contribution to the achievement of SDGs
by Furukawa Electric Group

Narrow Spectral Linewidth Integrable Tunable Laser Assemblies for Digital Coherent Optical Communications

Hiroyuki Ishii[*1], *Akihisa Kondo*[*1], *Masayoshi Kimura*[*1], *Yosuke Terada*[*2], *Kazuki Yamaoka*[*2], *Maiko Ariga*[*2], *Masayoshi Nishita*[*2], *Hiroyuki Koshi*[*2], *Tatsuro Kurobe*[*1]

ABSTRACT We have been developing narrow spectral linewidth integrable tunable laser assemblies used for digital coherent optical communication systems. In order to apply coherent optical communication technologies to communications for such as short distance metro areas, inter-data center, etc., a compact and low power consumption wavelength tunable laser source that can be installed in pluggable optical transceivers, etc. is required. In addition, an expansion of the wavelength bandwidth from the original C band to the extended C band and L band is required. In order to meet these requirements, we have been developing Distributed FeedBack (DFB) laser array type tunable lasers and tunable lasers monolithically integrating the Distributed Bragg Reflector (DBR) and the ring reflector. In addition, we have started to study ultra-narrow spectral linewidth tunable lasers for the next generation ultra-high speed and large capacity systems. In this paper, we will introduce the status of these developments.

1. INTRODUCTION

The introduction of Wavelength Division Multiplexing (WDM) technologies at the beginning of this century greatly increased the transmission capacity of optical communication systems. Initially, fixed wavelength light sources were used, but they have been replaced by tunable lasers[1)]. The practical application of widely tunable lasers that can oscillate at any wavelength in the wavelength band used, for example C band, has eliminated the need for an inventory of spare optical transceivers for the number of wavelengths needed as a backup in case of failure in the fixed wavelength case. Therefore, instead of fixed wavelength light sources, tunable lasers rapidly have become popular. At that time, the standard for the subassembly Integrable Tunable Laser Assembly (ITLA) that adds a control circuit to a tunable laser, was established by the Optical Internetworking Forum (OIF)[2)], and it has become popular as a standard interface.

In the 2010s, when the transmission speed per wavelength exceeded 10 Gbit/s, a digital coherent optical communication technology has been introduced. Since the coherent optical communication uses the phase information of light, the phase noise must be small. In other words, a narrow spectral linewidth is required. In order to meet this requirement, efforts have been made to narrow the linewidth of various tunable lasers. In addition, in recent years, there has been a movement to introduce digital coherent optical communication systems not only for long distance communications but also for short distance metro/access areas and inter-data centers, which requires miniaturization and low power consumption of light sources. For example, progress is being made in the development of compact light sources that can be installed in compact pluggable optical transceivers such as the Octal Small Form-factor Pluggable (OSFP) and the Quad Small Form-factor Pluggable Double Density (QSFP-DD).

We have been developing ITLAs for digital coherent optical communications that meet these requirements for high performance, compact size, and lower power consumption. Until now, we have developed a micro-ITLA using an Arrayed Waveguide Grating-Distributed Reflector (AWG-DR) laser array type tunable laser, which is monolithically integrating the AWG multiplexer in a DR laser array that integrates a DFB laser and a DBR. Also, we have developed a nano-ITLA using a DBR/ring type tunable laser, which is a monolithically integrating a ring reflector behind the gain area and a DBR and a Semiconductor Optical Amplifier (SOA) in front of the gain area for smaller pluggable optical transceivers. We will report on the structure and characteristics of these devices. In addition, we have started to study an external cavity laser in order to realize an ultra-narrow linewidth light source with a linewidth of 50 kHz or less, which is required for the next generation optical communication. We will also report on its progress.

[*1] Photonics Laboratory, Research & Development Division
[*2] Fitel Products Division

2. PERFORMANCE REQUIRED FOR WAVELENGTH TUNABLE LASERS

At first, we will describe wavelength tuning range, optical output power, and linewidth, which is the basic performances required for tunable lasers.

2.1 Tuning Range and Optical Output Power

As a tunable laser, the most basic specification is the tuning range. Basically, the laser should be able to cover the entire wavelength/frequency grid used in WDM optical communication systems. Of course, it must operate in both single longitudinal and transverse modes, and the Side Mode Suppression Ratio (SMSR) must be 45 dB or more. For the conventional C band (1529 to 1567 nm), the tuning range to cover the entire band (about 100 channels on a 50 GHz grid) is about 40 nm. However, in recent years, the demand for extended C band (1524 to 1573 nm, wavelength bandwidth approx. 50 nm) and L band (1565 to 1625 nm, wavelength bandwidth approx. 60 nm) has also emerged to expand the transmission capacity. Since the gain bandwidth from inter-band transitions in semiconductors is relatively wide, it is not too difficult to cover these many wavelengths.

For the optical output power, the fiber output power of about 15 to 19 dBm is required. Long distance communications using Erbium-Doped Fiber Amplifiers (EDFAs) do not require so much optical output power, but rather high output power characteristics may be required for relatively short distance systems that do not use EDFAs.

2.2 Linewidth – Laser Structure Design for Narrow Linewidth

We mentioned the importance of linewidth as a light source for digital coherent optical communications. In the first practical 25 Gbaud polarization multiplexed Quadrature Phase Shift Keying (QPSK) system with 100 Gbit/s per wavelength, the typical linewidth specification was 500 kHz or less. Later, however, since the multi value degree, such as 16 Quadrature Amplitude Modulation (QAM), and the high baud rate have been progressing, the linewidth specification has become stricter. Currently, the linewidth of 100 to 300 kHz or less are often required.

In this section, we will explain the linewidth. The linewidth $\Delta\nu$ of a semiconductor laser is expressed by the theoretical formula of Schawlow-Townes, modified by Henry[3],

$$\Delta\nu = \frac{{v_g}^2 n_{sp} q(\alpha_m + \alpha_i)^2}{4\pi\eta_i(I - I_{th})} K_z(1+\alpha^2)\Gamma_z^2 \qquad (1)$$

where v_g is the optical velocity in the laser medium, n_{sp} is the inversion distribution parameter, q is the elementary charge, α_m is the mirror loss, α_i is the internal loss, I is the operating current, and I_{th} is the threshold current. η_i is the internal quantum efficiency, K_z is the Petermann factor, α is the chirp parameter. Γ_z is the confinement factor for the active area in the total laser cavity, and is expressed by

$$\Gamma_z = \frac{n_a L_a}{n_a L_a + f_{ext} n_p L_p} \qquad (2).$$

Where, L_a and L_p are the lengths of the gain area and the external waveguide, respectively, n_a and n_p are their equivalent refractive indexes for each, and f_{ext} is the optical coupling coefficient between the gain area and the external waveguide.

Using the above equation, the linewidth $\Delta\nu$ is calculated for the mirror loss α_m and the result is shown in Figure 1. In the case of a DFB laser, Γ_z=1, but in a configuration in which an external waveguide or external resonator is integrated, Γ_z<1. In the case of a DFB laser, the mirror loss can be reduced by increasing the cavity length. An example of changing the cavity length L of a λ/4 shifted DFB laser is shown in the figure (Γ_z=1). By extending the cavity length from 450 μm to 1200-1500 μm, the mirror loss can be reduced from 52 cm^{-1} to 15-20 cm^{-1}, and this indicates that the linewidth of 1 MHz or more can be reduced to 300 kHz or less. In an external cavity laser, the linewidth is narrowed in proportion to the square of the active area confinement factor Γ_z. This is because a spontaneous emission light, which is the source of noise, does not mix with the laser light in the external waveguide portion. For example, when Γ_z is set to 1/3, it is possible to reduce the linewidth by about one order of magnitude even with the same mirror loss. Therefore, it can be said that the external cavity laser has a structure that makes it easy to narrow the linewidth.

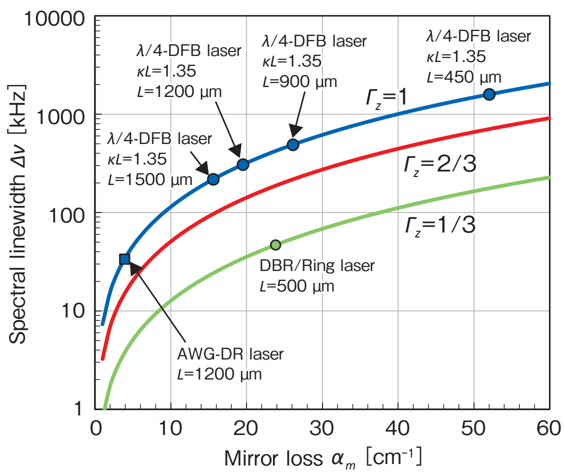

Figure 1 Calculated values of the spectral linewidth.

3. ARRAY TYPE WAVELENGTH TUNABLE LASER

3.1 DFB Laser Array

We, at first, developed a DFB laser array type tunable laser[4] and have been improving its performance based on its structure. The DFB laser array achieves a wide tuning range by monolithically integrating multiple DFB lasers with different wavelengths. For example, if the temperature of a DFB laser is changed by 35°C, the wavelength changes by about 3.5 nm, so if 12 lasers with wavelengths differing by 3.5 nm each are used, a wavelength tuning width of 3.5 x 12 = 42 nm can be obtained. The narrow linewidth of the DFB laser array was first achieved by increasing the cavity length. As explained in the previous chapter, the linewidth can be reduced as well as the mirror loss α_m by lengthening the cavity. In the Intensity Modulation-Direct Detection (IM-DD) system with a transmission rate of 10 Gbps, since there was no linewidth requirement, a resonator length of 400 to 500 μm was used and the linewidth was around 2 MHz. For digital coherent optical communications, the cavity length has been extended to approximately 1200 to 1500 μm, and the linewidth of 300 kHz or less has been achieved[5), 6)].

3.2 AWG-DR Laser Array

As the multi-value degree of multi-level modulation increases from QPSK to 16 QAM and 64 QAM in order to increase the signal speed, the linewidth of 100 kHz or less became a requirement. In order to meet this issue, we have developed an AWG-DR laser array chip, which is monolithically integrating further an AWG multiplexer in front of a DR laser array that integrates a DBR behind a DFB laser, as shown in Figure 2 (a)[7), 8)].

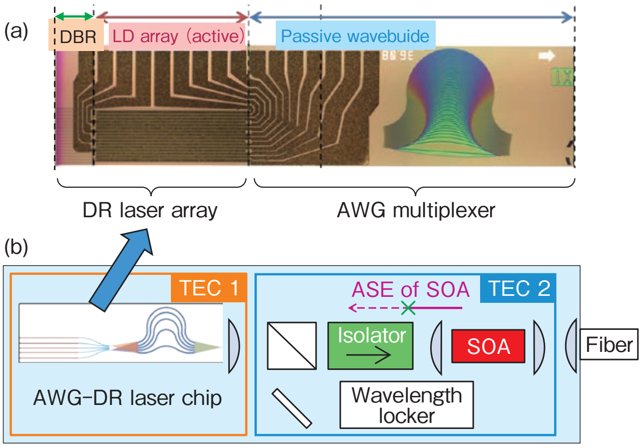

Figure 2 **Chip picture of the AWG-DR laser array (a) and the structure of the wavelength tunable laser module (b).**

By integrating the DBR behind the DFB laser to form a DR laser array structure, the mirror loss and threshold current are reduced, and a narrower linewidth has been achieved. The AWG is monolithically integrated as a multiplexer that combines the optical output from this DR laser array into one optical path. Conventional DFB laser arrays use an M x 1 Multi-Mode Interferometer (MMI) as a multiplexer, but while the MMI has a low wavelength dependence, there was an issue to cause theoretically a 1/M combining loss. Monolithically integrated AWGs can achieve higher coupling efficiency by taking advantage of wavelength selectivity, and a higher output power can be achieved by increasing the optical input power to the SOA. Figure 1 shows the design values of the AWG-DR laser, which is expected to have a linewidth of less than 100 kHz, corresponding to the reduction of the mirror loss and the threshold current.

In a tunable laser module using this AWG-DR laser array chip, as shown in Figure 2 (b), the SOA is separated from the laser chip as a separate chip, and an isolator is inserted between them to prevent the linewidth degradation caused by the spontaneous emission light from the SOA being mixed into the laser chip. In addition, the fact that the SOA can operate at low temperature by controlling independently from Laser chip is also contributing to the high output.

Figure 3 shows the optical output characteristics of the AWG-DR laser array type wavelength tunable laser module overlaid for 16 lasers, and Figure 4 shows the linewidths of each laser at the maximum and minimum operating temperatures. The fiber optical output of 19 dBm or higher and the linewidth of 100 kHz or lower are achieved[8), 9)]. Since a DR laser array that does not jump in principle is used, features of excellent controllability and reliability are obtained. Using an AWG-DR laser array module, we have developed a micro-ITLA with the control circuit described below, and it is being used in an actual system. Since the AWG-DR laser array module performs wavelength tuning by controlling the laser chip temperature with a ThermoElectric Cooler (TEC), the laser chip needs to operate in a wide temperature range. Therefore, there are some disadvantages with the power consumption and the difficulty of further miniaturization due to the separation of the SOA.

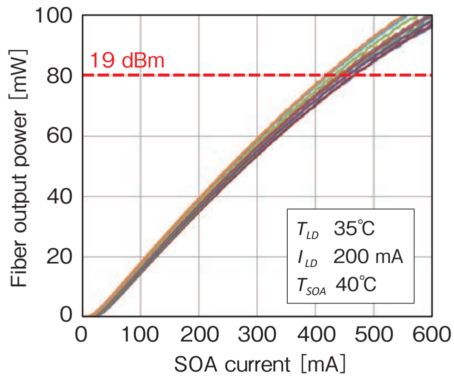

Figure 3 **Optical output power characteristics of the AWG-DR laser array module.**

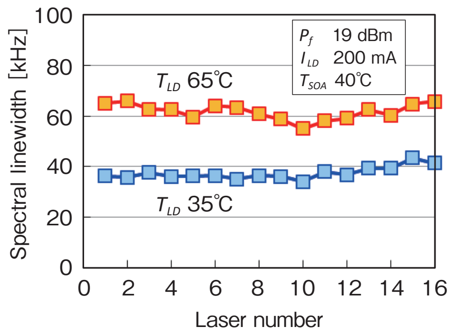

Figure 4 **Spectral linewidth characteristics of the AWG-DR laser array module.**

4. DBR/RING LASER

4.1 Monolithically Integrated Laser Chip for Compact ITLA

In order to realize a compact ITLA that can be installed in small pluggable optical transceivers such as QSFP-DD etc., we have developed a DBR/ring laser chip with a ring reflector behind the single gain area and monolithically integrating the DBR and the SOA in front, as shown in Figure 5[9), 10)].

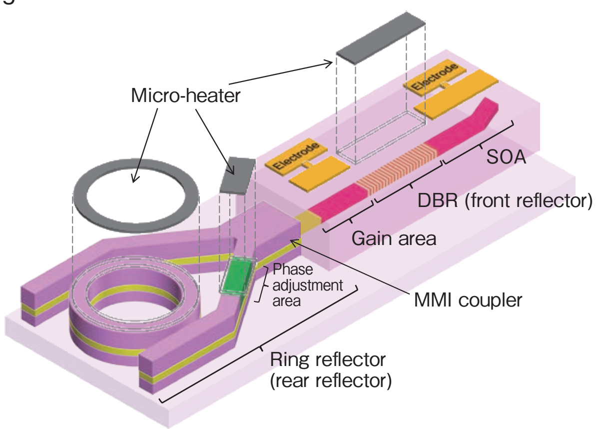

Figure 5 Schematic diagram of monolithically integrated DBR/ring laser chip.

Figure 6 shows the calculation results of the reflection spectrum of the DBR and the ring reflector for each, which are overlaid, and the calculation results of the synthetic reflection spectrum that determines the mirror loss of the resonator. In this example, it is designed to generate eight reflection peaks by applying a phase modulation to the DBR diffraction grating pattern. On the other hand, the ring reflector has a reflection spectrum with infinitely periodic peaks. Since the intervals between the reflection peaks of both are designed to be slightly different, the synthetic reflection spectrum has a maximum reflectivity at the wavelength where the reflection peaks of both coincide, making it possible to oscillate at a single wavelength. By controlling the temperature using microheaters formed on the ring reflector and the DBR, the reflection spectrum for each can be shifted, making it possible to select a wide range of wavelengths using the Vernier scale principle. In addition, the rear ring reflector can be miniaturized than the DBR, and the heater power consumption can be reduced compared to a DBR laser with DBRs at the front and rear. In addition, since the front DBR has a finite number of reflection peaks, the wavelength range can be limited. The feature of this device is to combine each feature. The SOA is monolithically integrated in front of the DBR, making it possible to control the optical output by the SOA current.

In addition, since a reflector composed of a passive waveguide is provided outside the gain area, a narrow linewidth operation is possible due to the external cavity effect. Figure 1 plots the mirror loss vs. linewidth of the DBR/ring laser in the ideal case, where linewidths below 100 kHz are expected.

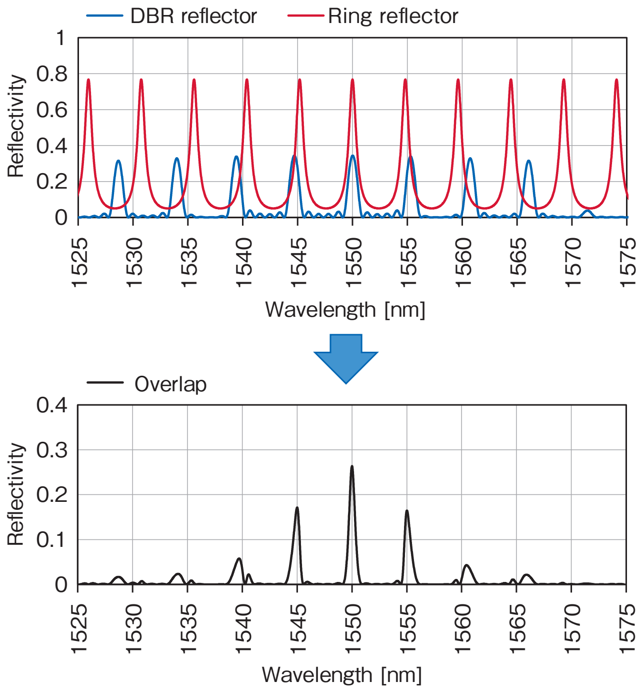

Figure 6 Calculated results of the reflection spectrum of DBR and ring reflector and the synthetic spectrum.

Figure 7 shows the structure and external view of a miniaturized laser module using a monolithically integrated DBR/ring laser chip and a Planer Lightwave Circuit (PLC) wavelength rocker. The size of the laser chip is 3 mm (L) × 0.35 mm (W). The wavelength rocker PLC consists of a SiO_2-ZrO_2 core with a large specific refractive index difference (Δ) of approximately 5%, which allows a small minimum bending radius of the waveguide and a compact size of 1.7 mm (L) × 2.5 mm (W).

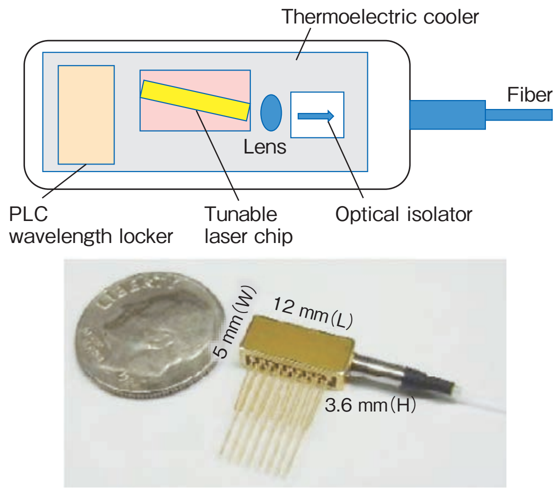

Figure 7 Structure and picture of the DBR/ring laser module.

Figure 8 shows the linewidth characteristics of the DBR/ring laser module. A compact tunable laser with 17 dBm fiber output and the linewidth of less than 100 kHz in the entire C band has been achieved. The miniaturization of the chip and the wavelength rocker has also led to a significant reduction in the size of the ITLA, realizing a nano-ITLA that can be installed in the compact pluggable optical transceiver described below (see Figure 12).

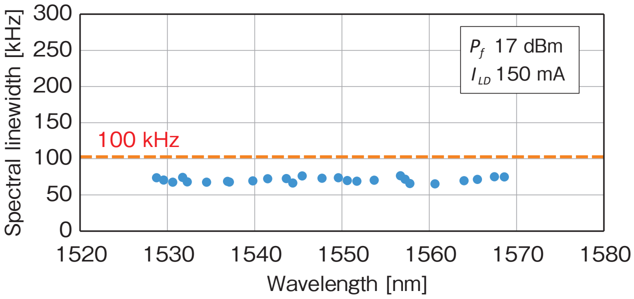

Figure 8 Spectral linewidth of the DBR/ring laser module.

4.2 Expansion of Tuning Range for Extended C band

Next, we improved the ring reflector and the DBR in order to achieve the tuning range corresponding to the extended C band[11]. Initially, we have been using a 2 × 2 MMI for the branching of the ring reflector, but have decided to use a 1 × 2 MMI. Since the beat length is short, the ring circuit length can be shortened, which makes it possible to increase the Free Spectral Range (FSR) and can expand the operating wavelength of the tunable laser. In addition, by using a 1×2 MMI, the MMI width can be designed to be wider, improving the fabrication tolerance. In addition, the FSR of the DBR was expanded and the number of reflection peaks was reduced from 8 to 7, further improving the fabrication tolerance. In other words, the FSR of both the ring and the DBR was increased to correspond the extended C band.

Figure 9 shows the calculation results of the wavelength dependence of excess losses caused by the width error of the 2×2 MMI and the 1×2 MMI. The target value of input and output waveguide widths was set to 1.2 μm, and the spacing between the two waveguides was set to 0.9 μm. The dimensions of the 2 × 2 MMI and 1 × 2 MMI were calculated using a formula based on the beat length theory[12]. On top of that, the width error was set to a range of –100 nm to +100 nm, and in the 2×2 MMI, an error of 0.1 μm causes a maximum excess loss of 1.5 dB in the extended C band (1524 to 1573 nm). A ring reflector that effectively passes through the MMI three times would cause a loss of 4.5 dB, impairing its function as a reflector. On the other hand, in the 1×2 MMI, this excess loss is reduced to 0.5 dB, and it is expected that the processing tolerance will be improved.

Figure 10 shows a ring reflector using the fabricated 1 × 2 MMI. Evacuation waveguides to remove back propagating light were designed to be provided on both sides of the connecting waveguide of the MMI waveguide, one coupled to the slab waveguide and the other to the scatterer for processing.

A DBR/ring laser corresponding to the extended C band was fabricated by combining a DBR and a ring reflector using a 1 × 2 MMI.

Figure 11 shows the measurement results of the lasing spectrum and the chip optical output superimposed at each operating point of the DBR/ring laser for the extended C band. The single mode lasing with SMSR>45 dB and the output power of 18 dBm or more was obtained in the 54 nm range covering the extended C band.

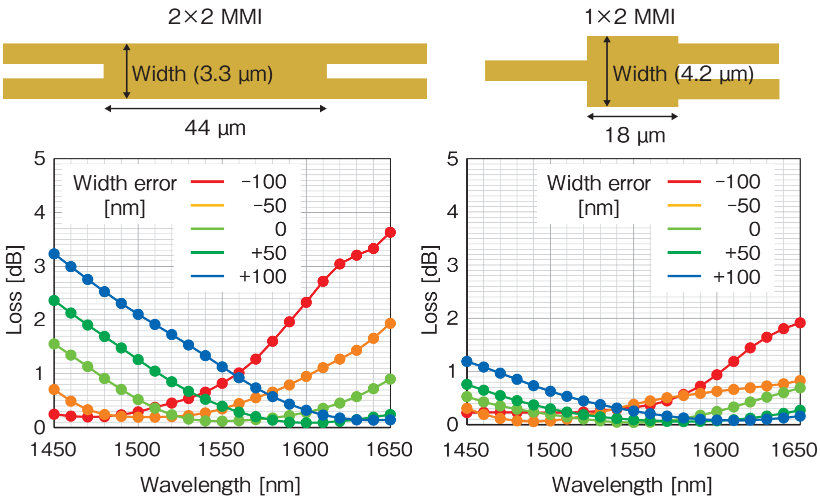

Figure 9 Calculated results of the loss characteristics for the 2x2 MMI (left side) and the 1x2 MMI (right side).

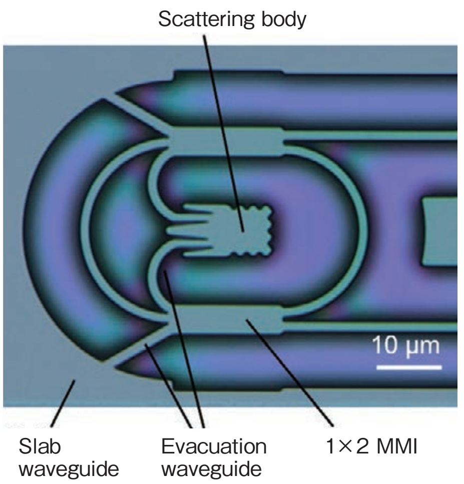

Figure 10 Surface picture of the ring reflector.

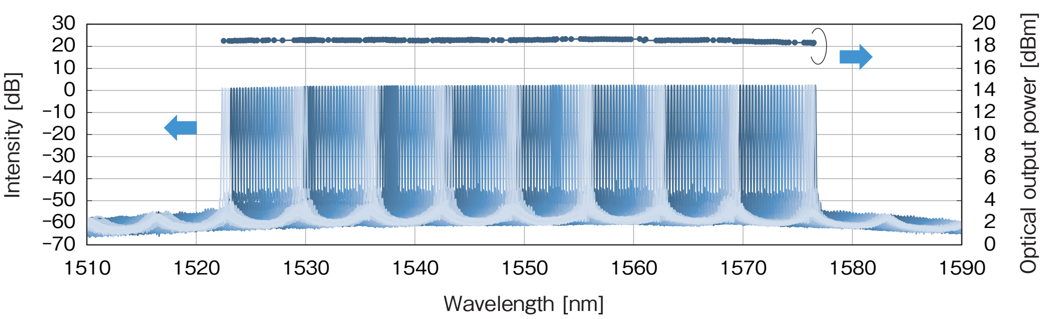

Figure 11 Lasing spectrum and optical output of an extended C band DBR/ring laser using 1x2 MMI.

5. CONTROL CIRCUIT FOR THE ITLA AND MINIATURIZATION

As mentioned in the introduction, the OIF defines a standard for subassemblies of ITLAs that add control circuit to tunable lasers. Using an ITLA that conforms to this standard, the user can control the laser output by commands via a serial interface. Various parameters such as current, temperature, wavelength locker PD, etc. to obtain the desired wavelength and the light intensity of the laser are stored in memory, and the desired operation can be obtained by control commands. In other words, the advantage of this standard is that the user no longer needs to be aware of the different types of tunable lasers with different control methods.

In response to the demand for miniaturization of optical transceivers, progresses have been made in miniaturization and low power consumption of ITLAs. Figure 12 shows the picture of each generation of ITLA. Initially, the ITLA was manufactured at the time of 10 Gbit/s IM-DD, but to accommodate small pluggable optical transceivers such as the C Form-factor Pluggable (CFP) and CFP2, the standardization of micro-ITLA, which is smaller than ITLA, was established as a standard for subassemblies[13]. The array type tunable laser module mentioned above has been installed in a micro-ITLA and put into practical use. Although not yet standardized, a nano-ITLA, which is an even smaller light source subassembly, has been developed by installing the DBR/ring laser module mentioned above. Power consumption has also been reduced to about half that of the original ITLA.

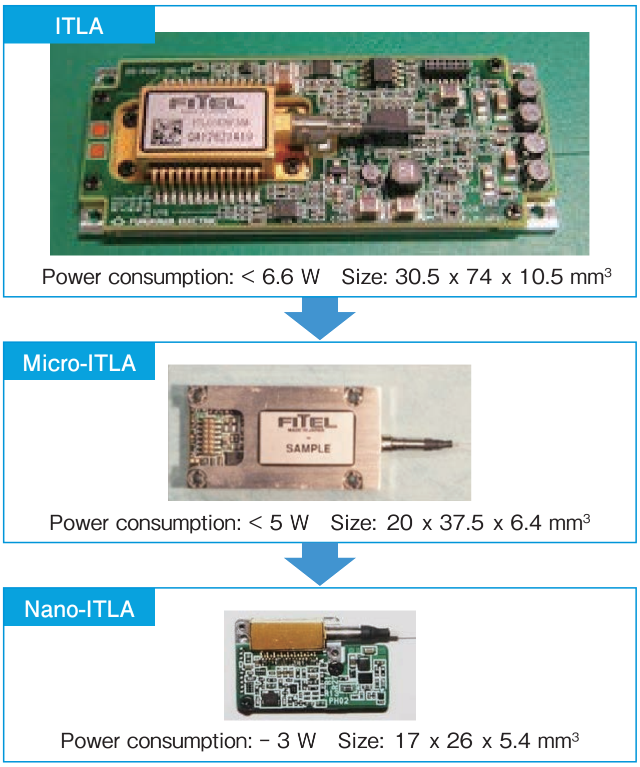

Figure 12 Transition of the ITLA miniaturization.

Figure 13 shows the control circuit block diagram of the nano-ITLA, which consists of each control circuit for the CPU and the Gain, SOA, DBR, Ring, Phase, and TEC. Driving conditions for each control circuit are determined, by calculating appropriate target values and correction parameters based on the command information from the host module. Each current control circuit for the DBR and the Ring controls the heater power to a constant level based on the set wavelength information. The phase current control circuit controls the output wavelength to a constant level based on the wavelength locker PD value. The SOA current control circuit controls the optical output power to a constant value based on the PD monitor power. The TEC control circuit controls the temperature to a constant level based on the thermistor resistance.

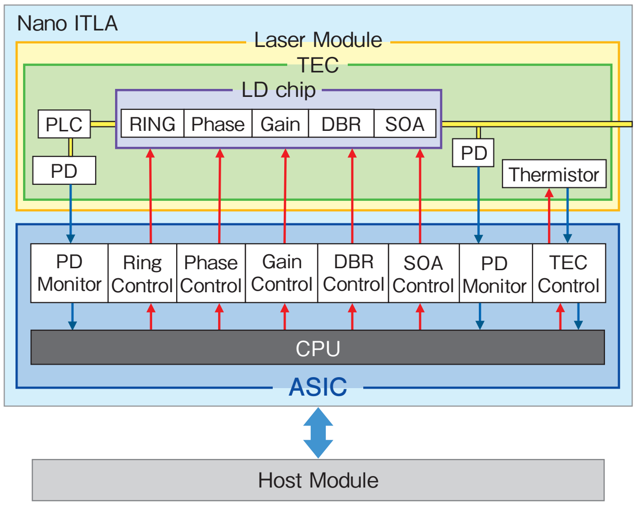

Figure 13 Block diagram of a nano-ITLA control circuit.

In order to fit into the size of the nano-ITLA while maintaining the functionality of the conventional ITLA, in addition to the adoption of an Application Specific integrated Circuit (ASIC) that integrates the laser control function into a single IC, we optimized the electrical filter configuration, and carried out the substitution of control circuit functions with software.

6. STUDY OF THE ULTRA-NARROW TUNABLE LASER FOR THE NEXT GENERATION

In response to the recent explosive demand for increased data transmission capacity, signal baud rates are increasing significantly, and although still in the research stage, cases exceeding 200 Gbaud have been reported. At such high baud rates, since the amount of dispersion compensation by Digital Signal Processor (DSP) increases, the linewidth requirement for the light source will also become stricter. We have started to study a new external cavity wavelength tunable laser with a linewidth of 50 kHz or less as the next generation ITLA, and we are reporting the progress here[14].

Figure 14 shows the structure of an external cavity tunable laser composed of a semiconductor chip with monolithically integrated DBR and SOA in front of the gain area and an external reflection mirror and Si etalon behind the gain area. In terms of structure, instead of the ring reflector of the previously mentioned DBR/ring laser, an external mirror and a Si etalon are arranged. Since the length of the external cavity portion is increased, the confinement factor Γ_z of the active area becomes smaller, and a narrower linewidth can be expected.

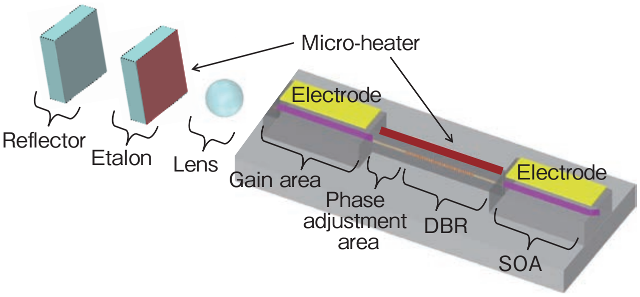

Figure 14 Configuration of the external cavity tunable laser using the external etalon and mirror.

Figure 15 and Figure 16 show the measurement results of the lasing spectrum and the linewidth of the fabricated external cavity laser, respectively. Covering the entire C band, narrow linewidth characteristics of 50 kHz or less with an SMSR of 50 dB or more are obtained. Thus, the external cavity laser has excellent linewidth characteristics. However, there are some issues, such as the fact that the mounting is more complicated than that of monolithic types, and that the wavelength control becomes sensitive because the longitudinal mode interval becomes narrower due to the longer cavity length. These issues need to be resolved before practical use.

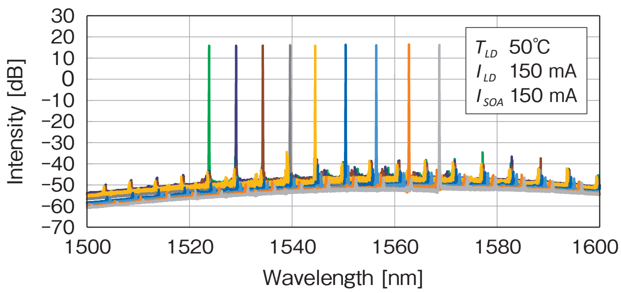

Figure 15 Lasing spectrum measurement results of the external cavity laser using external etalon and mirror.

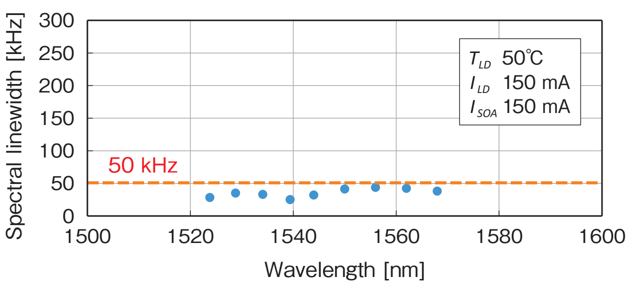

Figure 16 Spectral linewidth measurement results of the external cavity laser using external etalon and mirror.

7. CONCLUSION

We described the tuning range, optical output power, and linewidth, which are important requirements for tunable lasers for digital coherent optical communications, and explained how to reduce the linewidth in various laser structures using the theoretical equation of Schawlow-Townes. We have developed a micro-ITLA using a monolithically integrated AWG-DR laser array module as a narrow linewidth and high-power source, and have achieved high power operation of 19 dBm and narrow linewidth operation below 100 kHz by reducing mirror loss due to the DR structure and coupling loss due to AWG, and by adopting the SOA isolation structure. We have developed a nano-ITLA using a DBR/ring- laser module that can be installed in compact pluggable optical transceivers, and have achieved 17 dBm optical output and linewidth characteristics below 100 kHz. As an improved version of the DBR/ring laser for the extended C band, a DBR/ring reflector laser using a 1 × 2 MMI as a ring reflector was fabricated, and a light source covering the extended C band was realized. Furthermore, for future ultra-narrow linewidth light sources, we fabricated a prototype external cavity laser consisting of a semiconductor chip monolithically integrating gain area, DBR, and SOA, an external mirror, and an external etalon, and obtained narrow linewidth characteristics of less than 50 kHz. We believe that this laser is promising as an ultra-narrow linewidth light source in the future. We have been improving the performance of wavelength tunable lasers in order to meet the highly evolving system requirements, and we will continue to improve the performance of light sources as a fundamental technology to support high speed and large capacity optical communications.

ACKNOWLEDGMENT

A part of these research results was supported by National Institute of Information and Communications Technology (NICT) Japan under commissioned research (JPJ012368C04501) .

REFERENCES

1) J. Buus, M. C. Amann, and D. J. Blumenthal: “Tunable laser diodes and related optical sources”, 2nd ed. Piscataway, NJ, USA: Wiley-IEEE, 2005.
2) Implementation Agreement for Tunable Laser, IA # OIFITLA-MSA-01.3, July, 2015. https://www.oiforum.com/wpcontent/uploads/2019/01/OIF-ITLA-MSA-01.3.pdf
3) C. H. Henry: “Theory of the linewidth of semiconductor lasers,” IEEE J. Quantum Electron., vol. 18, no. 2, 259-264, Feb. 1982.
4) Tatsuro Kurobe, Tatsuya Kimoto, Kengo Muranushi, Toshikazu Mukaihara, Maiko Ariga, Nozomu Matsuo, and Akihiko Kasukawa: “Development of Full-Band Tunable Laser”, Furukawa Electric Review, No. 33, 2008.
5) H. Ishii, K. Kasaya, and H. Oohashi: “Narrow spectral linewidth operation (<160 kHz) in widely tunable DFB laser array”, Electron. Lett., vol. 46, no. 10, 714–715, 2010.

6) T. Kimoto, G. Kobayashi, T. Kurobe, T. Mukaihara, and S. Ralph: "Narrow linewidth tunable DFB laser array for PDM16QAM transmission", presented at the OptoElectron. Commun. Conf./ Photon. Switching, Kyoto, Japan, 2013, Paper MK2-6.
7) G. Kobayashi, K. Kiyota, T. Kimoto, and T. Mukaihara: "Narrow linewidth tunable light source integrated with distributed reflector laser array", presented at the Optical Fiber Conf., 2014, Tu2H.2.
8) T. Suzuki, K. Kiyota, S. Okuyama, Y. Inaba, M. Ariga, and T. Kurobe: "Tunable DFB Laser array combined by monolithically integrated AWG coupler", presented at the Int. Semicond. Laser Conf., Kobe, 2016, TuC3.
9) M. Nishita, Y. Higa, N. Matsubara, J. Hasegawa, K. Yamaoka, M. Ariga, Y. Inaba, M. Kimura, M. Wakaba, M. Yoshida, K. Maruyama, S. Okuyama, T. Suzuki, H. Ishii, V. Mikhailov, R. Sefel, and Y. Kawakita: "Compact tunable DBR/ring laser module integrated with extremely-high-Δ PLC wavelength locker", presented at the Opt. Fiber Commun. Conf., San Diego, CA, USA, 2020, Paper M2A.6.
10) Masayoshi Nishita, Noritaka Matsubara, Junichi Hasegawa, Kazuki Yamaoka, Maiko Ariga, Yusuke Inaba, Masayoshi Kimura, Masaki Wakaba, Masahiro Yoshida, Kazuomi Maruyama, Toshihito Suzuki, Hiroyuki Ishii, Yasumasa Kawakita: "The Development of a Nano-ITLA for Digital Coherent Datacenter Interconnect", Furukawa Electric Review, No. 52, 2021.
11) Y. Terada, Y. Isobe, H. Abe, T. Sakai, M. Nishita, H. Ishii, and T. Kurobe: "Monolithic DBR/Ring Tunable Laser Employing 1x2 MMI-coupled Ring Resonator", presented at the Int. Semicond. Laser Conf., Matsue, 2022, MC-02.
12) P. A. Besse, M. Bachmann, H. Melchior, L. B. Soldano and M. K. Smit: "optical bandwidth and Fabrication Tolerances of Multimode Interference Couplers", J. Lightwave Technol. 12 (1994), 1004-1009.
13) Implementation Agreement for Tunable Laser, IA # OIF Micro-ITLA 01.1, July, 2015. https://www.oiforum.com/wpcontent/uploads/2019/01/OIF-Micro-ITLA-01.1.pdf
14) K. Yamaoka, M. Ariga, Y. Terada, V. Mikhailov, H. Ishii, T. Kimura, and T. Kurobe: "Narrow linewidth DBR laser incorporating with an intra-resonator etalon", presented at the Int. Semicond. Laser Conf., Orlando, 2024, WD1.