Monolithically Integrated Tunable Three-Section All-Active DBR Laser Diodes With 30 nm Tuning Range

Shaokang Chen, Dechao Ban, Yu Liu, Ming Li, *Member, IEEE*, and Ninghua Zhu, *Member, IEEE*

***Abstract*—We present a monolithically integrated three-section all-active AlGaInAs/InP tunable distributed Bragg reflector (DBR) ridge waveguide laser diode that uses thermal tuning mechanism and mode-hopping tuning principle to achieve wide-range wavelength tuning. It is similar to the traditional three-section DBR laser structure, including a gain section, a phase section, and a DBR grating section. The difference is that the phase section and the DBR section incorporate the same active quantum well structure as the gain section. In this case, weak effective refractive index changes of the three active sections affected by the current injection will occur since the carrier density is clamped by the threshold gain condition of the DBR laser diode. Despite this limitation, a noncontinuous tuning up to ∼30 nm (1564–1594 nm) can be observed using only current injection at a constant temperature of 25 °C. Significant thermal effects occurred during the tuning process. In addition, a discontinuity is introduced in the tuning because it does not contain a passive region for phase adjustment. However, the device still provides a stable single longitudinal mode output with nine channels, a wavelength spacing of about 4 nm, and a side mode suppression ratio (SMSR) of more than 30 dB. Furthermore, the DBR laser diode can be easily fabricated utilizing the conventional distributed feedback laser diode fabrication process without secondary epitaxy and heater metal. The all-active DBR laser diode will be expected to be applied in the coarse wavelength division multiplexing (CWDM) systems with the advantage of low cost.**

***Index Terms*—Semiconductor lasers, laser tuning, tunable semiconductor lasers, thermal tuning.**

I. Introduction

SINCE the introduction of fiber optic communication systems in the last century, especially the invention of Erbium-doped fiber amplifier (EDFA) and the promotion of wavelength division multiplexing (WDM) technology, fiber optic communication technology has made significant progress, and the information rate has become higher and higher. In WDM systems, more channels mean more information capacity can be transmitted. For example, [1] used three tunable lasers combined as an ultra-wideband (S, C, and L bands) WDM signal (50 GHz spacing, 272 channels) and achieved 150 Tbps information transmission rate in single mode single core fiber [1]. As the central optical transmitting component in WDM systems, the wider tuning range of tunable lasers means more channels can be multiplexed, which is essential for the information capacity enhancement of WDM systems.

Common tunable lasers mainly include external cavity tunable lasers and monolithic integrated tunable lasers. Typical external cavity structures include Littrow and Littman structures [2]. Typical monolithic integrated laser diodes include distributed Bragg reflector (DBR), sampled grating distributed Bragg reflector (SG-DBR), and super-structure-grating distributed Bragg reflector (SSG-DBR) laser diodes [3]. Both the reported external cavity lasers and monolithically integrated lasers can achieve a large tuning range. Cosimo (2022) presented a novel hybrid integrated tunable laser based on a high-power InP RSOA and thick SiN microring resonators, which achieves a tuning range of around 45 nm, a high output power over 40 mW, high side mode suppression ratio (SMSR) (>50 dB), and narrow linewidth of around 5 kHz [4]. Takuma (2022) demonstrated a heterogeneously integrated widely tunable laser using a lattice filter and ring resonator on Si photonics platform with a wavelength tuning of 1529 to 1561 nm and a less than 40 kHz Lorentzian linewidth [5]. Kuankuan (2023) demonstrated a narrow linewidth electro-optically tuned multi-channel interference (MCI) widely tunable semiconductor laser based on carrier injection, which obtains a quasi-continuous tuning range over 48 nm and a less than 320 kHz Lorentzian linewidth [6]. Jia Xu (2020) reported a III-V/silicon hybrid wavelength-tunable laser covering the application-rich wavelength region of 1647–1690 nm with an estimated linewidth of 0.7 kHz [7]. Paul A (2022) reported a new class of ultra-wideband wavelength tuning, ultra-low noise Integrated Coherent Tunable Laser (ICTL), This laser showed record integrated laser performance: 118 nm wavelength tuning, covering S-, C- and L-bands, with Lorentzian linewidth <100 Hz, and with excellent relative intensity noise (RIN) of ≤−155 dBc/Hz [8]. Yuyao (2022) presented a III-V/Si3N4 hybrid-integrated tunable laser, and the laser shows a record of ∼170-nm tuning range with a side mode

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suppression ratio above 64 dB and an intrinsic linewidth below 2.8 kHz [9]. Moon-Hyeok (2020) reported the integration of SG-DBR lasers that show a 53 nm tuning range in the C band from 1533 nm to 1586 nm with 40 dB SMSR [10]. External cavity lasers are composed of gain chips and various external cavity structures. The gain chip provides optical gain, and the external cavity structure realizes wavelength selection through the vernier effect. Generally, a wide range of wavelength tuning can be realized by changing the cavity length caused by heat. Although it is composed of discrete devices, the current package can also be miniaturized in the form of Nano-ITLA [11]. The monolithic integrated tunable laser diode has more advantages in terms of integration, and its basic structure includes the active section, the phase control section, and the grating section. The basic principle is that the active section provides optical gain, and the phase control section can adjust the phase change of the laser diode and then change the effective refractive index of the laser to achieve wavelength tuning. The DBR grating area is responsible for wavelength selection. Applying different currents will change the effective refractive index of the grating section and then change the Bragg wavelength to achieve tuning. The grating section can also use unique structures, such as sampling gratings and superstructure gratings, to achieve a wider wavelength tuning range.

Thermally tuned monolithically integrated laser diodes have also been extensively studied. [12] demonstrated a thermally widely tunable buried heterostructure laser diode with distributed feedback, and this device requires only two tuning currents for a 43 nm quasicontinuous wavelength tuning [12]. Oh Kee (2018) reported a novel structure that is capable of wide wavelength tuning in the DBR laser diode with a single grating mirror with a tuning range of 26 nm (i.e., 7 nm for plasma tuning and 19 nm for heater tuning) [13]. Su Hwan (2019) reported a 1.3-μm and 10-Gbps tunable DBR laser diode with a tuning range of more than 15 nm at a heater injection current of ∼100 mA [14]. [15] demonstrated a narrow-linewidth thermally tuned MCI laser integrated with a semiconductor optical amplifier (SOA) and spot size converter (SSC), and the MCI laser achieves a tuning range of more than 42.5 nm and Lorentzian linewidth below 100 kHz [15]. The above results show that thermal tuning has an excellent tuning potential.

This paper reports a monolithically integrated AlGaInAs/InP tunable all-active three-section DBR ridge waveguide laser diode based on thermal tuning principle. It is similar to the traditional three-section DBR laser structure, including three parts: a gain section, a phase section, and a DBR grating section. The difference is that the phase section and the DBR section use the same active quantum well structure as the gain section. Generally, the wavelength tuning of the three-section DBR laser diode can be achieved at about 10 nm [3]. But this laser diode has good tuning ability. During the tuning test, it was found that each electrode injection current will cause the wavelength to change. Therefore, the wavelength behavior of laser diodes under different current combinations was investigated. The test results under all current combinations were counted, and a discontinuous tuning up to ∼30 nm (1564–1594 nm) was observed at a constant temperature of 25 °C. In total, the all-active three-section laser diode provides a stable single longitudinal mode output with nine channels, a wavelength spacing of ∼4 nm, and an SMSR of over 30 dB.

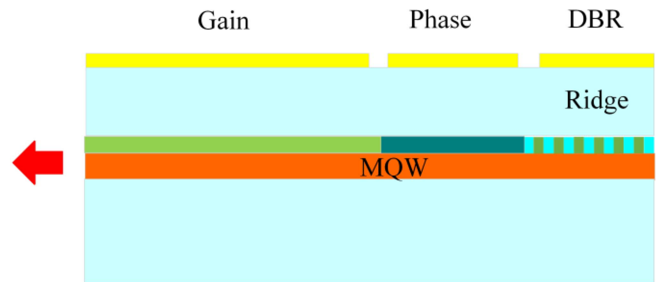

Fig. 1. Schematic diagram of the proposed monolithic integrated three-section tunable all-active DBR laser diode.

II. Device Design and Tuning Mechanism

A. Device Design

Fig. 1 shows a schematic diagram of the structure of the demonstrated monolithic integrated three-section tunable all-active DBR laser diode. Similar to the typical three-section laser diode chip structure, the three sections of the fabricated laser diode are also called the gain section, phase section, and DBR section. Unlike the typical three-section laser diode, the phase and DBR sections do not use the Butt-joint regrowth method or quantum well intermixing (QWI) technique to fabricate passive regions. However, they contain the same multi-quantum well (MQW) structure that can generate optical gain as the gain section. The device was prepared on a 2.5-inch 1550 nm wafer with AlGaInAs/InP material system. The laser diode was designed with a ridge waveguide structure with a width of 2 μm and a height of 1.8 μm. The length of the gain section is 450 μm, the length of the phase section is 150 μm, the length of the DBR section is 100 μm, and an electrical isolation section of 20 μm is positioned between each section. The width of the cleavage channel is 20 μm, and both facets of the laser diode are uncoated. The DBR grating was fabricated using electron beam lithography (EBL) with a grating period of 238 nm. Because the fabricated DBR grating is uniform, besides EBL, it can also be produced by holographic exposure lithography. The manufacturing process of the all-active DBR laser diodes is relatively simple and requires only the manufacturing process level of the ordinary DFB laser diodes.

B. Tuning Mechanism

The lasing wavelength of the laser diode is closely related to the effective refractive index, and the laser diode needs to satisfy the threshold gain condition and the phase resonance condition before lasing. Referring to Fig. 1, the phase condition that needs to be satisfied in the cavity of the three-section all-active DBR semiconductor laser diode is given by [16]

$$\lambda_{\mathrm{m}} = \frac{2(n_g L_g + n_p L_p + n_{\mathrm{DBR}} L_{\mathrm{DBR}})}{m} \tag{1}$$

where m is the longitudinal mode number, λ_m is the lasing wavelength that satisfies the phase condition, n_g is the effective refractive index of the gain section, n_p is the effective refractive index of the phase section, $n_{\rm DBR}$ is the effective refractive index of the DBR section, L_g is the length of the gain section, L_P is the length of the phase section, $L_{\rm DBR}$ is the effective length of the DBR section. As can be seen from (1), for semiconductor laser diodes, the cavity length varies negligibly, and the lasing wavelength is mainly related to the effective refractive index of the laser diodes.

There are three main ways to change the effective refractive index of tunable semiconductor laser diodes: free-carrier plasma dispersion effect (FCPD) [17], quantum-confined Stark effect (QCSE) [18], and thermo-optic effect [19]. The typical DBR laser diodes developed from the above effect can include the passive phase section and the passive grating section represented by the multi-section DBR laser diodes [3], the fast tunable QCSE laser diodes with reverse biased electric field [18], and the thermally tunable semiconductor laser diodes [12], [20]. Considering the operation principle of semiconductor laser diode, the effective refractive index is usually related to the injected carrier density. After the laser diode reaches the threshold current, the carrier density and gain in the active region cannot increase without limitation with the increase of the injection current but will be clamped near the threshold. This also means that the current injection in the active region has little effect on the effective refractive index. Therefore, the phase and grating section of conventional DBR laser diodes are passive structures. Due to the free carrier plasma dispersion, the effective refractive index changes significantly in the passive region.

Generally, the wavelength tuning of the three-section DBR laser diode can be achieved at about 10 nm. QCSE laser diode applied reverse bias voltage caused a slight change in the effective refractive index, usually can achieve about 7 nm wavelength tuning. Although QCSE laser diodes have a small tuning range, they can produce faster wavelength responses because they are not limited by carrier lifetime. The change in effective refractive index due to the thermo-optical effect can also significantly change the wavelength of the laser diode. Unlike the free-carrier plasma effect, the wavelength of the laser diode is red-shifted as the current increases and the temperature rises. The primary sources of temperature changes include the heat generated by various non-radiative recombination during laser diode operation (the conversion efficiency of laser diodes is only 30%) and the heat generated by the Joule effect.

The all-active laser diode proposed in this paper has an active structure in each section. The carrier density will be clamped near the threshold value when the laser diode operates, which results in little change in the effective refractive index due to the free carrier plasma dispersion effect. The tuning of this laser diode relies mainly on thermal tuning and mode-hopping tuning. Without considering the laser cavity length variation, (1) is solved to obtain [16]

$$\frac{\Delta\lambda_{\rm m}}{\lambda_m} = \frac{\Delta n_g L_g + \Delta n_p L_p + \Delta n_{\rm DBR} L_{\rm DBR}}{n_g L_g + n_p L_p + n_{\rm DBR} L_{\rm DBR}} - \frac{\Delta m}{m} \qquad (2)$$

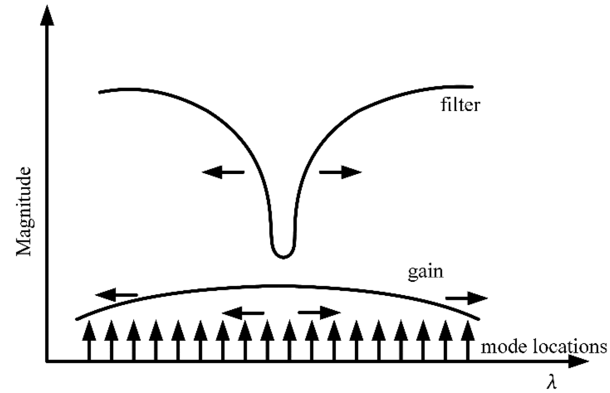

Fig. 2. The mode shift process of the proposed all-active DBR laser diode. The process combines the gain spectrum shift, the grating reflection spectrum shift and the cavity mode position shift caused by the temperature change.

where $\Delta\lambda_m$ is the change of wavelength shift, Δm is the change of longitudinal mode shift. (2) shows how the laser diode mode shifts. It is mainly composed of two parts: one is the change of the effective refractive index of the three sections due to the temperature increase, which is called the thermo-optic effect, and the other is the change of the operation mode in the cavity caused by the temperature change, which is called the mode-hopping tuning.

Fig. 2 illustrates in detail the mode shift process of the proposed all-active DBR laser diode. The lasing wavelength shift caused by temperature changes mainly includes two parts. One is the overall shift of the gain spectrum toward longer wavelengths due to the increase in temperature and the narrowing of the active layer bandgap (The Bandgap Shrinkage Effect). The other is the slight change in the effective refractive index (thermo-optical effect) and the geometry of the laser diode caused by the temperature increase. In this change, the effective refractive index satisfying the laser resonance phase condition changes, causing a shift in the lasing mode. The sources of the temperature variation of the laser diode are mainly non-radiative recombination and Joule heat generated by current injection. But the use of heater metal is expected to give better results, as in the work of R. Todt (2005) [12]. Since each part of the fully active DBR laser diode contains an active structure, the current injection in different parts of the area will cause the laser to generate a large amount of heat. The heat will cause the laser lasing wavelength to change. The all-active DBR laser diode proposed in this paper has three dimensions that can be adjusted by the temperature change, which combines the gain spectrum shift, the grating reflection spectrum shift caused by the temperature change, and the cavity mode position shift caused by the temperature change. Because the all-active DBR laser does not contain a passive phase control region, it will not be able to achieve large-scale continuous tuning but more mode-hopping tuning caused by temperature changes.

C. Packaging and Testing

To ensure good heat dissipation and mechanical stability of the device during the test, the monolithic integrated tunable

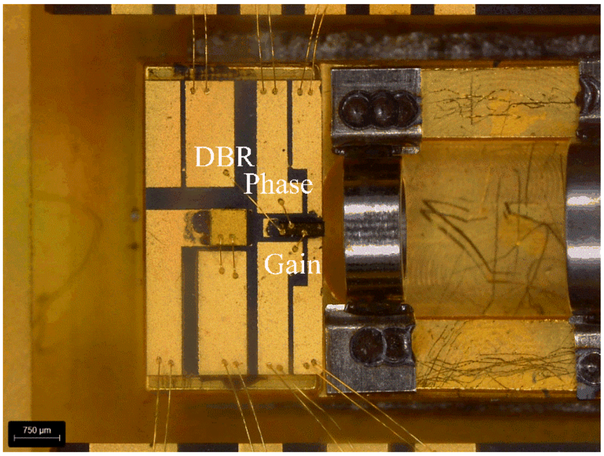

Fig. 3. The figure of the 14-pin all-active DBR laser.

all-active DBR laser diode proposed in this paper is packaged with a 14-pin butterfly structure, as shown in Fig. 3. The package has a built-in thermoelectric cooler (TEC) cooler and aluminum nitride (AlN) heat sink, giving the chip better heat dissipation capability. The electrical connection adopts 25 μm gold wire bonding, and using two leads can reduce the series resistance and carry a larger operating current. The package does not contain an optical isolator. In order to reduce the performance degradation of the laser caused by reflected light, a fiber isolator is added during the test. When the same batch of the laser diode is tested without a fiber isolator, the SMSR performance will significantly deteriorate despite the excellent wavelength tuning performance. Better results are expected with built-in optical isolators in the package.

The packaged laser was fixed using a standard 14-pin butterfly test fixture. The LDC501 Laser Diode Controllers controlled temperature and current. Its temperature control accuracy is $\pm$0.01 °C, and its current accuracy is $\pm$0.05 mA. During the test, each current source must share the ground. The resolution of the spectrum analyzer is 0.02 nm, and the test mode is the MID mode, which can obtain more clearly visible side modes. In addition to the spectrum tuning test, the PIV curve before chip packaging was tested by a semiconductor parameter analyzer, and the power of the laser was tested by an optical power meter. In the wavelength tuning range test, the TEC temperature was stabilized at 25 °C, the injection current in each section was changed sequentially, and the spectral data under different currents were recorded. The phase noises of the different laser diodes were also tested using the OE4000 Laser Linewidth/Phase Noise Analyzer. The key parameters of the equipment's used for experiments are shown in Table I.

III. Result and Discussion

We first tested the spectrum properties at different current levels by maintaining the law of the single variable and varying only the injection current of a single section.

TABLE I
The Key Parameters of the Equipment's Used for Experiments

Equipment	Key Parameters	Set Value
LDC501 Laser Diode Controllers	Temperature setting Temperature control mode Laser control mode	25℃ CT mode CC mode
AQ6370D Optical Spectrum Analyzer	Span Measurement resolution Measurement sensitivity	10 nm 0.02 nm MID
OE4000 Laser Linewidth/Phase Noise Analyzer	10-100 Hz RBW 100-1k Hz RBW 1k-10k Hz RBW 10k-100k Hz RBW 100k-1M Hz RBW	300 mHz 3 Hz 30 Hz 300 Hz 3 kHz

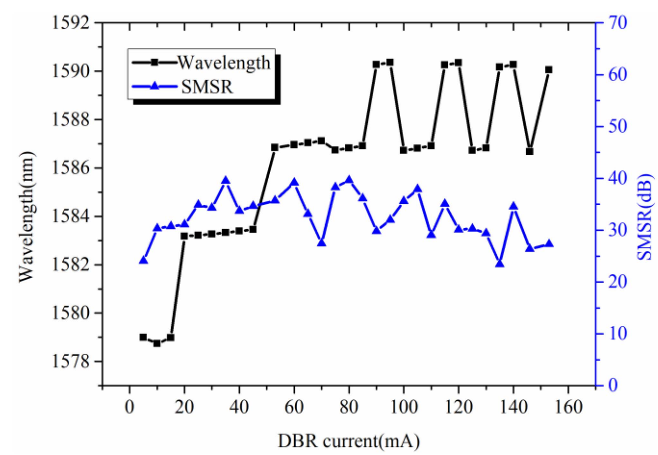

Fig. 4. The wavelength variation of all-active DBR laser diode at different DBR currents. The current in the gain current is fixed at 50 mA, the phase current is fixed at 0 mA.

A. DBR Current Changes

Following the experience of conventional types of DBR laser diodes with passive grating regions, changing the current in the DBR section is expected to have a large tuning range, so the spectrum characteristics of changing the DBR current were studied first. The wavelength tuning range of the all-active DBR laser diode that only changes the DBR current was tested experimentally. During the test, the current in the gain current was fixed at 50 mA, the phase current was fixed at 0 mA, and only the current in the DBR section was changed. The length of the DBR region is 100 μm, and the maximum current of the injected DBR section can reach 150 mA, which is quite aggressive for the DBR section.

The test results are shown in Fig. 4. With the gradual increase of DBR current, the wavelength of the all-active laser diode slowly moves towards the long wavelength as the injected current increases, and the wavelength of the DBR laser diode will remain almost stable in a small range. The reason for the steady wavelength shift is that the temperature change from the current

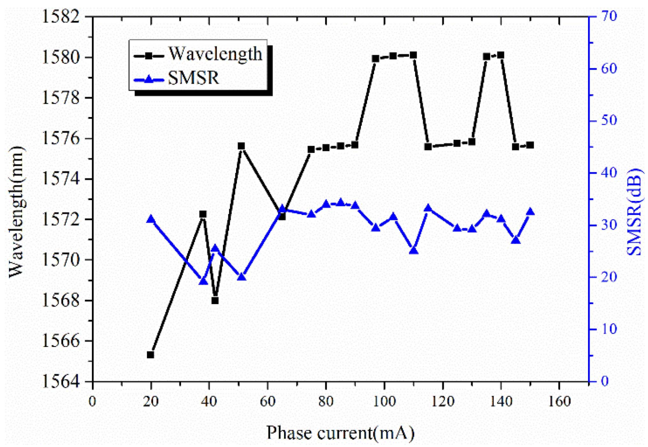

Fig. 5. The wavelength variation of all-active DBR laser diode at different phase currents. The current in the gain current is fixed at 15 mA, the DBR current is fixed at 8 mA.

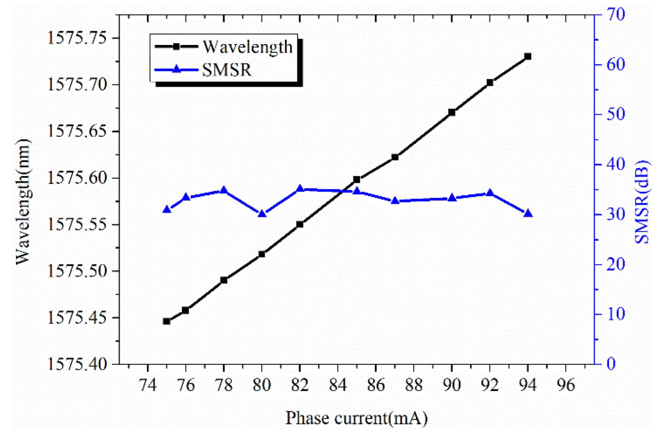

Fig. 6. The wavelength variation of an all-active DBR laser diode with a small range of phase current changes. The current in the gain current is fixed at 15 mA, and the DBR current is fixed at 8 mA.

injection is not enough to cause a mode-hopping in the laser diode. With the gradual increase of the DBR current, the lasing mode of the laser diode hops to the long wavelength direction. The mode spacing is about 4 nm. This behavior is the opposite of a DBR laser diode with a passive grating region. This behavior also shows that the wavelength change of the laser diode is mainly caused by thermal tuning. When the current of the DBR is further increased by about 90 mA, the wavelength of the laser diode does not increase without limit. This limitation is due to the deterioration of the laser diode's operating performance and the reduction of the internal recombination efficiency as the heat rises progressively, and the current level required to maintain the original lasing mode needs to be increased. Therefore, the wavelength of the laser diode hops between the two modes at high current injection. The spectrum behavior of the DBR current variation at different gain current levels also confirms this characteristic. The SMSR of the laser diode can be stable above 30 dB when the DBR injection current is small, which meets the requirements of standard optical transmitters. However, as the temperature increases, the SMSR also suffers performance degradation. Adding an optical isolator inside the package is expected to improve this result.

B. Phase Current Changes

The traditional DBR laser diode with a passive phase structure can control the phase change so that the wavelength can be tuned in a small range. The all-active DBR laser diode proposed in this paper cannot change the phase in the cavity because the phase section is also active. However, it can still achieve a wide range of tuning. The tuning mechanism in the phase region is the same as that in the DBR region, relying on heat to cause changes in the cavity mode. The wavelength tuning range of the laser diode that only changes the phase current has been experimentally tested, and the test results are shown in Fig. 5. During the test, the current in the gain section is fixed at 15 mA, the current in the DBR section is fixed at 8 mA, and only the phase current is changed at large intervals. The test results show that with the increase of the phase current, the wavelength of the laser diode also shows a change rule of hopping to the long wavelength direction as a whole. Furthermore, when the phase current is higher than 90 mA, it shows the same mode switching rule as the large DBR current when the DBR current changes in the previous section DBR Current Changes. However, when the current is between 30–60 mA, the wavelength of the laser diode shifts in the short wavelength direction. This phenomenon is because when the current level is near the threshold current, there is intense mode competition in the cavity, which causes mode-hopping switching. For example, it can be found that the SMSR at some wavelengths is only 19 dB and multiple modes appear in the spectrum. The main reason for this result is the absence of an optical isolator in the package. This reason may also be related to the low coupling coefficient of the grating and the short grating length. As the current increases above the threshold current, the cavity lasing mode of the laser diode tends to be stable, and the SMSR can be maintained above 30 dB.

Fig. 6 shows the wavelength change behavior of the all-active DBR laser diode for a slight change of the phase current. The results show that with a slow increase of the phase current, the wavelength of the laser diode continuously shifts toward the long wavelength direction nearly linearly and slowly while maintaining an excellent single longitudinal mode characteristic. This result again validates the mechanism of thermal tuning. Similar to the DBR section, the heat change generated in the phase section is not enough to cause the cavity lasing mode to hop. Hence, the laser diode maintains continuous thermal tuning in a small range. The test results show that although the SMSR performance of the laser diode deteriorates at some operating points of mode switching, it maintains good single longitudinal mode performance for most operating points in the middle of the mode.

C. Gain Current Changes

The structure of the gain section is the same as that of the phase section, but the length is much longer than that of the phase section. Therefore, the gain section should show the same

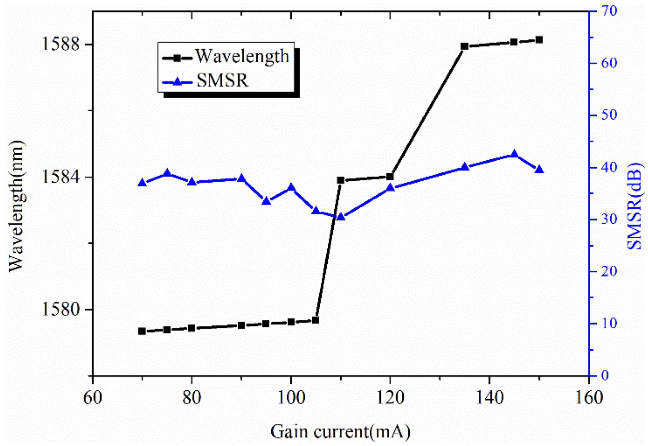

Fig. 7. The wavelength variation of all-active DBR laser diode at different gain current. The current in the phase current is fixed at 13 mA, the DBR current is fixed at 0 mA.

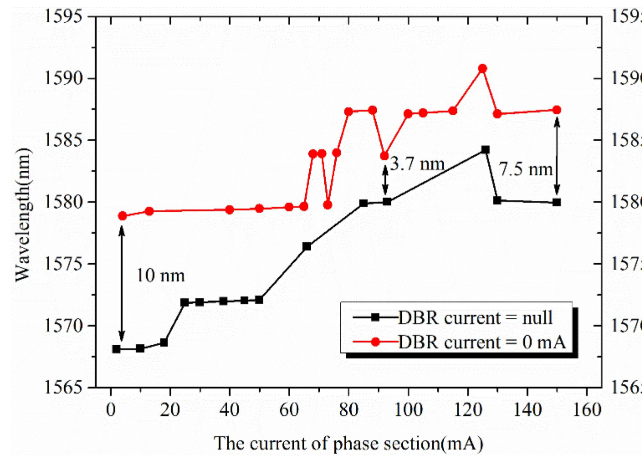

Fig. 8. The wavelength tuning characteristics of the DBR electrode at different current injection states (zero bias and null). The gain current is fixed at 50 mA, and only the phase current is changed.

change law as the phase section. The wavelength tuning range of the laser diode with only changing the gain current has been experimentally tested, and the test results are shown in Fig. 7. During the test, the phase current is fixed at 13 mA, the DBR current is fixed at 0 mA, and only the gain current is changed at large intervals. The results show that, similar to the phase section and the DBR section, the lasing wavelength of the laser diode shifts to the long wavelength direction with the current increase. However, as the current changes, there are only three switching modes in the laser diode. This result is because although the structure of the gain section is the same as that of the phase section, the gain section length is 450 μm, which is 4.5 times the phase section length. The thermal accumulation generated by the gain current injection is not as good as in the phase section.

The above three test results show that the effect of changing the current in the three parts is similar. The essence of all of them is the heat-induced hopping of the cavity lasing mode in the laser diode toward the long wavelength.

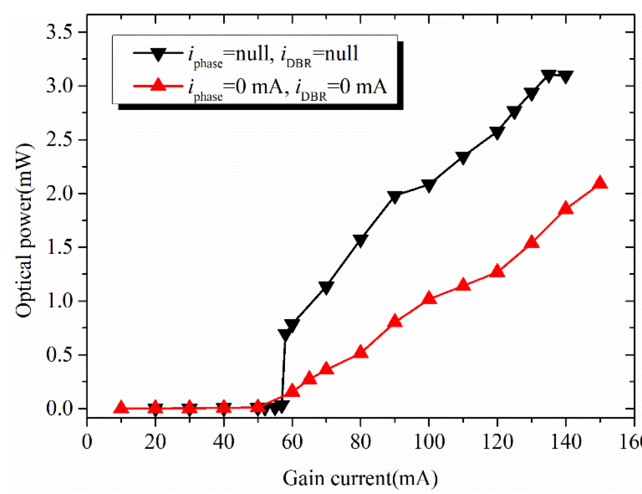

Fig. 9. The PI curves of the all-active DBR laser diode in different electrode bias states. "0 mA" means that the injection current is 0 but there is still a bias voltage; "null" means that the current is completely disconnected.

D. Zero Bias Current and Null

During the test, we unexpectedly found a more significant change in the wavelength of the all-active DBR laser diode between when the current injection is 0 mA (there is a bias voltage) and when no current is applied (the current is completely disconnected, called null). The wavelength tuning characteristics of the DBR electrode at different current injection states (zero bias current and null) were tested. The test results are shown in Fig. 8, where the gain current is fixed at 50 mA, and only the phase current is changed. The results show that the wavelength shifts to the short wavelength direction at null than at zero bias with the same current, and the shift range can be up to 10 nm.

To further analyze the reason for the above phenomenon, we tested the PI characteristic curves of the all-active DBR laser diode in different electrode bias states, and the test results are shown in Fig. 9. The results show that when no current is applied (null), the optical power level of the laser diode is higher, and its slope efficiency is greater than that of the current. Moreover, the optical power will increase cliff-like near the threshold current ($\sim$55 mA). When no current is applied (null), since each section of the quantum well has the same structure, the place where no current is applied is equivalent to a photodetector in a state of zero bias voltage. This section absorbs the photons generated in the gain section at this time, and the carriers accumulate at the PN junction until it is saturated. Afterward, the laser light of stimulated emission is generated when the inverted population in the active region reaches the lasing condition. However, the photons in the cavity are no longer absorbed after lasing, so the PI curve becomes smooth. So, the cliff-like increase is mainly caused by early photon absorption. There is a bias voltage when the injection current in the DBR section is 0 mA. The photogenerated carriers in the cavity cannot accumulate due to the influence of the electric field, and the DBR section always absorbs the photons in the cavity. Thus, the overall losses increase, resulting in lower slope efficiency.

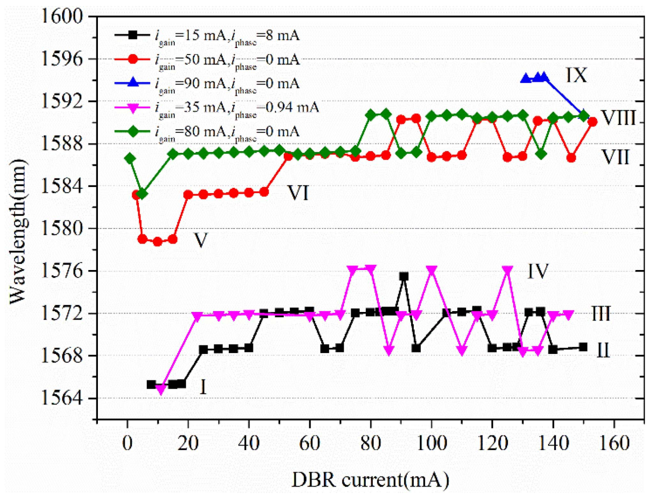

Fig. 10. The wavelength tuning characteristics of the all-active DBR laser with varying currents in the three sections.

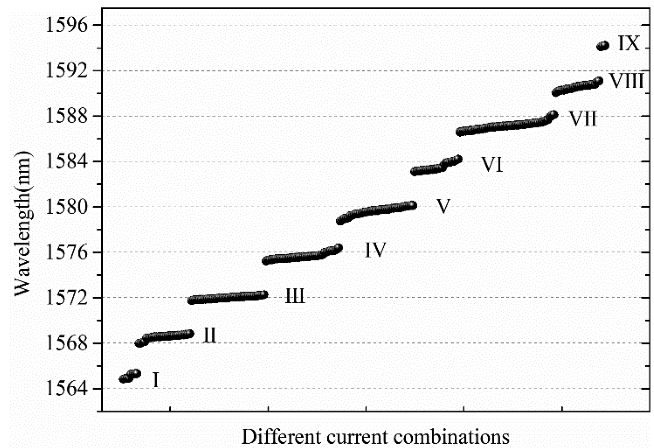

Fig. 11. The wavelength distribution combining all test results. This figure is the statistical distribution of the test under the condition that the currents of the three electrodes are all changed, and it is obtained by arranging all the test results in order from small to large.

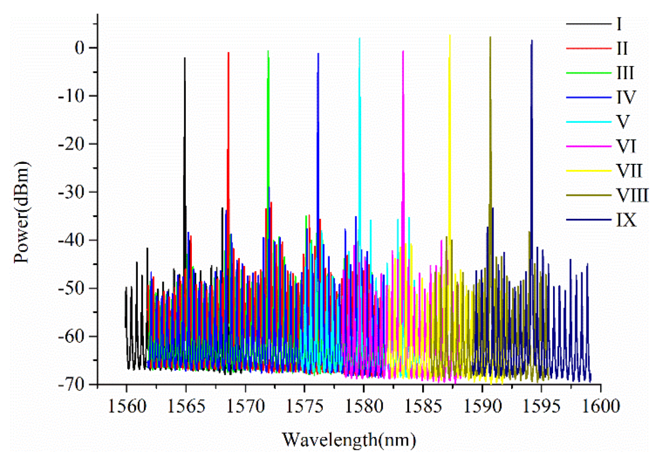

Fig. 12. The laser spectrum test results of each typical operating mode, and each mode can achieve stable over 30 dB longitudinal mode output.

Therefore, the reasons for the wavelength shifts in different current injection states are discussed in the following cases. When the current is disconnected (null), the accumulation of electrons and holes is equivalent to electron injection due to the effect of photo-generated carriers, causing the lasing wavelength to shift to a shorter wavelength. When the injection current is 0 mA (zero bias current), the discharge leads to the disappearance of the accumulated photo-generated carriers, and the lasing wavelength returns to the long wavelength case. However, when a large current is injected, the thermal effect is significant, and the lasing wavelength shifts to the long wavelength direction as the current increases.

E. Overall Analysis

The proposed all-active DBR laser diode consists of only one cavity with a total length of 780 μm, which relies on a grating for mode selection. Unlike the early coupled-cavity lasers in the 1980s, the three-section structure is connected to each other, and there is no actual reflection facet. So, we can assume that the effect of the three sections of the current change is the same. The essence is the heat-induced hopping of the cavity lasing mode in laser diodes toward the long wavelength.

The wavelength tuning characteristics of the all-active DBR laser with varying currents in the three sections are investigated, as shown in Fig. 10. Fig. 10 shows some typical test results. It can be found that the laser diode can realize nine different output modes. Although there is a mode competition at the critical point of mode switching, each mode can achieve a stable single longitudinal mode output over 30 dB within a significant current fluctuation level. We performed extensive testing on the tuning range of all-active three-section laser diodes. Since the laser has three electrodes, the injection current of each electrode can change the wavelength, and the electrodes can also be without injection current. The wavelength distribution combining all test results is shown in Fig. 11. It can cover the wavelength tuning range of 30 nm(1564-1594 nm).It is worth noting that this figure is the statistical distribution of the test under the condition that the currents of the three electrodes are all changed, and it is obtained by arranging all the test results in order from small to large. Although slowly changing the injection current of a single electrode will cause the wavelength to move slowly and continuously, two adjacent wavelengths may not correspond to continuous changing currents, such as 1568.632 nm($i_{\rm gain} = 50$ mA, $i_{\rm phase} = 18$ mA, $i_{\rm DBR} =$ NULL) and 1568.640 nm($i_{\rm gain} = 15$ mA, $i_{\rm phase} = 8$ mA, $i_{\rm DBR} = 65$ mA) in Fig. 11. Although fully active three-segment DBR laser diodes cannot achieve large-scale continuous tuning, The wavelengths of different sub-intervals can be switched freely by pre-calibrating all test results as a database like external tunable cavity lasers. Fig. 12 shows the laser spectrum test results of each typical operating mode, and each mode can achieve stable longitudinal mode output. Since its tuning mechanism mainly relies on thermal tuning and mode-hopping tuning, continuous tuning cannot be achieved because it does not contain a passive region for phase control, so a ∼3.5 nm gap is generated.

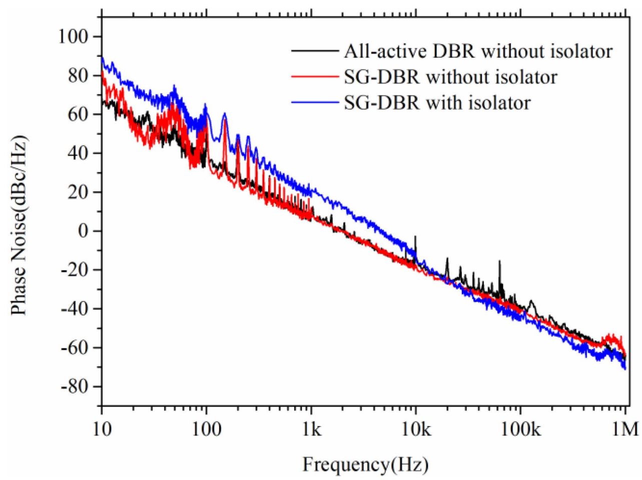

Fig. 13. The phase noise spectrum of all-active DBR laser without isolator, SG-DBR laser with isolator, and SG-DBR laser without isolator. The abscissa coordinate is logarithmic.

However, compared with typical SG-DBR and SSG-DBR laser diodes, it has a lower cost and has particular application potential in CWDM systems in the future.

F. Phase Noise Measurements

The phase noise of the laser is one of the key parameters of the long-distance data transmission system. The phase noise of semiconductor lasers is mainly composed of spontaneous emission noise and 1/f noise. The phase noise spectrum of the proposed all-active DBR laser without isolator was tested using OE4000 Laser Linewidth/Phase Noise Analyzer, and the test results are shown in Fig. 13. For comparison, the phase noise spectrum of commercial SG-DBR laser without isolator and SG-DBR laser with isolator were also tested. The abscissa coordinate in Fig. 13 is logarithmic. All-active DBR laser exhibit typical 1/f noise at low frequencies, as shown in Fig. 13. The estimated linewidths of the above lasers are obtained by the Phase Noise Analyzer through the phase noise test results from 10 Hz to 1 MHz. The estimated linewidth of the all-active DBR laser is ∼7.26 MHz, the estimated linewidth of the SG-DBR laser without an isolator is ∼6.79 MHz, and the SG-DBR laser with an isolator is ∼1.85 MHz. All parts of the proposed laser are active, and there is no special structural design for narrowing linewidth. Therefore, its linewidth test results are similar to those of DFB lasers, and the value is on the order of MHz. Since there is no optical isolator, the linewidth of the test will be further increased. However, it can be estimated that the linewidth should be around 1 MHz, referring to the test results of the SG-DBR laser. Currently, the latest reported results of tunable lasers in other schemes are below 100 kHz [4], [5], [7], [8], [9], [21], and there is still a big gap compared with them. In the next step, we will optimize the epitaxial process, optimize the grating structure, and use the multi-period-delayed feedback [22] technology to narrow the linewidth.

IV. Conclusion

In this paper, we present a monolithically integrated three-section all-active AlGaInAs/InP tunable DBR ridge waveguide laser diode. The tuning mechanism of this laser diode is theoretically analyzed, and the process of its mode shift is explained in detail. The analysis results show that the source of the laser diode wavelength variation is mainly the Joule heat generated by non-radiative recombination and current injection. In this paper, only the injection current of a single section is changed to analyze the spectrum characteristics at different current levels. It is found that the wavelength of the laser diode will shift to the long wavelength as a whole. Secondly, the behavior of the DBR section with or without injected current was studied. The results show that at the same current, the wavelength shifts to the shorter wavelength direction at null than at zero bias, and the shift range can reach 10 nm. Finally, a discontinuous tuning up to ∼30 nm (1564–1594 nm) was observed at a constant temperature of 25 °C using only current injection. It provides a stable single longitudinal mode output with nine channels, a wavelength spacing of ∼4 nm, and a side-mode suppression ratio of over 30 dB. Furthermore, the DBR laser diode can be easily fabricated utilizing the conventional distributed feedback laser diode fabrication process without secondary epitaxy and heater metal. The all-active DBR laser diode will be expected to be applied in the CWDM systems with the advantage of low cost.

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