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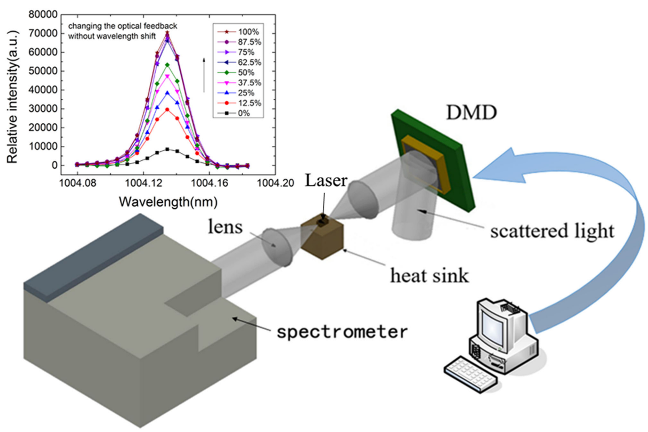

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Regulating the Single-Mode Lasing Intensity of Semiconductor Lasers Without Wavelength Shift

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Abstract: A simple method to regulate the single-mode lasing intensity of semiconductor lasers without wavelength shift is demonstrated in this paper. The basic component is a digital micro-mirror device (DMD), which can be taken as an adjustable two-dimensional grating by its special structure. The lasing peak wavelength and peak intensity are respectively regulated by the DMD angular position and the DMD setting. The lasing peak wavelength could be tuned over by rotating the DMD. Meanwhile, the lasing peak intensity could be regulated by the DMD setting, which generates optical feedback digitally. The regulating speed is very high (up to 10 kHz) and has no wavelength shift in the lasing mode, which is more stable and faster than the conventional method.

Index Terms: Semiconductor lasers, optical feedback, lasing mode regulation.

1. Introduction

The regulation of semiconductor lasers plays an essential role in numerous areas such as optical communication and environmental monitoring [1], [2]. Commonly, the laser intensity receivers have good performance under various conditions [3]. So the intensity regulation is widely used in lasers for its easy manipulation [4]. Thus, the intensity regulation method gets more and more attention in the laser research and application field [5].

Typically, changing the current injection is an effective way to regulate the lasing intensity, because the injection current can be easily manipulated by external power sources [6]. However, the injection current method has many inevitable disadvantages, such as the heat effect of current, which leads to red shift or blue shift in the lasing spectrum [7]. Facing this problem, many researchers proposed some practical solutions, such as the lasing wavelength stabilization using optical resonator, or using purely optical reference, or using optical feedback and so on. Among these methods, using the optical feedback is considered as an effective way to restrict the optical spectrum shift phenomenon [8]. Thus, many research groups used highly reflective mirrors to obtain the optical feedback in lasers. In order to achieve different optical feedback intensities, some research groups used mirrors with different reflectivities [9]. However, there are also large

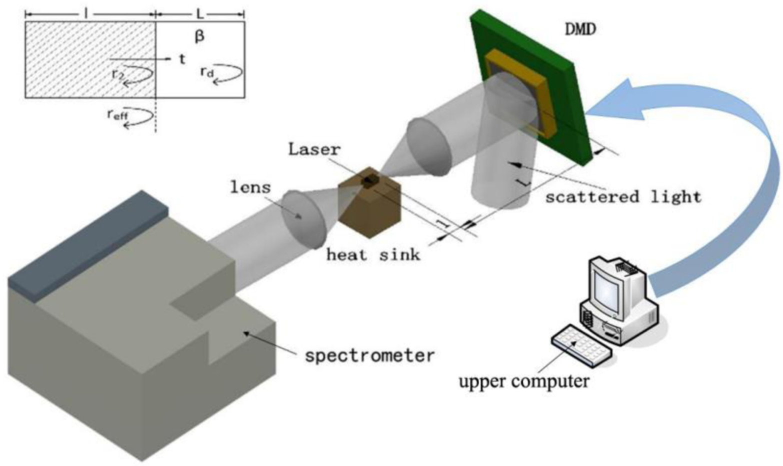

Fig. 1. Schematic structure of the laser regulation system.

disadvantages in these methods, for example, replacing mirrors could cause changes in the light path, which requires to be adjusted again, so that it is not convenient to be applied. Aiming at this problem, some other research groups put forward the method to change the output light intensity by the spatial light modulator (SLM) [10]. Although this method does not change the light path, it could only change continuously within certain section with slowly adjusting speed, which also limits its range of application. Herein, a novel method is proposed in this paper by adopting a digital micro-mirror device (DMD) as an optical feedback device, which could simply regulate the optical feedback intensity of semiconductor lasers within short time through the control software, without shifting the peak wavelength of the output single-mode lasing spectrum within certain range. In this way, the intensity regulation performance of semiconductor lasers could be improved greatly. In our method, we apply the DMD as an adjustable wavelength selector in this paper. This method is verified to be effective through experiments with reliable experimental results.

2. Experimental Setup and Theoretical Mode

The experimental setup in this study is illustrated in Fig. 1, where a laser diode, two lenses and a DMD are included. Herein, the DMD is connected to the upper computer to provide an adjustable reflection. The laser device adopted is an InAs/GaAs quantum dot (QD) laser diode with two uncoated cleaved facets. The semiconductor QD laser structures were grown on nominally (001) exact oriented n-type GaAs substrates by gas source molecular-beam epitaxy. The undoped active core consisted of five-stacked InAs QD layers embedded in 160 nm thick $Al_{0.15}Ga_{0.85}As$ layer. Ridge waveguide QD lasers with stripe widths of 6 μm, and stripe length of 1.5 mm was fabricated [11]. The threshold current is 186 mA, corresponding to the current density of 2089.4 A/cm^2. Multi-longitudinal-mode spectrum was recorded with peak wavelength located at about 1004 nm.

The key component in our method is the DMD, which is a digital micro-mirror device developed for digital light processing (DLP) by Texas Instruments. As a new type of optical switch matrix, it contains millions of micro mirrors, each of which could be controlled independently. The micro mirrors can be rotated $+12^\circ$ or -12° along the micro-mirror diagonal to an “on” or “off” state individually. In the “on” state, light from the laser diode is reflected back, resulting in optical feedback into the laser cavity. In the “off” state, the light is directed elsewhere, generating no optical feedback. Each micro mirror is square in shape with the size of 13.68 μm $\times$ 13.68 μm and the gap between them is less than 1 μm. Since the material of the micro-mirror surface is made of aluminum, it could effectively reflect the light with the wavelength from 400 nm to 2500 nm [12]. The DMD adopted in this experiment is Texas 0.7XGA DDR, containing 1024 $\times$ 768 micro mirrors. The angle of rotation of each micro mirror could be set by uploading the black and white bitmap with the pixel of 1024 × 768 to the upper computer software, enabling binary pattern rates of up to 10 kHz. For instance, to make all micro mirrors rotate +12° (or −12°), it is only to upload a whole white (or black) picture to the upper computer.

In the setup shown in Fig. 1, there are two optical cavities related to the lasing process, i.e., the internal cavity and external cavity, which are composed by three mirrors. The simplified two cavities are shown in the inset of Fig. 1, where the three mirrors are respectively the two uncoated cleaved facets and the DMD. Following the theoretical analyze reported in [13], the DMD and the diode facet near to the DMD can be considered as an equivalent virtual mirror, whose reflection coefficient is expressed as below:

$$\mathrm{r}_{eff} = \mathrm{r}_2 + \frac{t^2 r_d e^{-2j\beta L}}{1 + r_2 r_d e^{-2j\beta L}} \tag{1}$$

$$\beta = 2n\pi/\lambda, \mathrm{t} = 2\sqrt{nn'}/\left(n + n'\right) \tag{2}$$

$$r_d = \sqrt{\eta_c R_d}, r_2 = \sqrt{R_2} \tag{3}$$

where L is the external cavity length, r_2 and R_2 are the reflection coefficient and reflectivity of the cleaved facet, r_d and R_d the reflection coefficient and reflectivity of the DMD, r_eff the equivalent reflection coefficient of the equivalent virtual mirror, β the phase factor, t the transmission coefficient, n the refractivity of air, n' the refractivity of material in the internal cavity, and j is the imaginary unit, η_c represents the coupling losses which also include the lens absorption. Therefore, the system shown in Fig. 1 can be considered as having a laser cavity, which is composed by a cleaved facet and the virtual mirror. The most important feature of this system is that the reflection coefficient of the virtual mirror, r_eff, may be varied by adjusting the reflection coefficient of the DMD, r_d, as shown in Eq. (1).

In the general case, the reflection coefficient r_eff is a complex number, which takes into account the relative phase of the laser output field and of the field impinging back on the laser front facet after reflection on the external DMD. According to the definition and explanation of reflection, absolute value of r_eff is taken for calculation, while R1, R2, l and L are known and constant.

3. Methods and Results

Here we take the DMD as an adjustable optical feedback device to regulate the laser intensity. In view of the fact that each micro mirror of DMD can control its rotation angle with the software. The optical feedback intensity can be controlled by setting the ratio of rotated micro mirrors. Besides the size of each DMD micro mirror is very small, only 13.68 μm × 13.68 μm, far smaller than the diameter of the laser beam, which was about 10mm in this experiment. Thus, a number of micro mirrors could be considered as a unit and is extended to the overall DMD at certain rotation ratio. A periodic alignment structure was created by this setting, so as to achieve the objective of changing the DMD reflectivity [14]. Herein, the DMD adopted in this study has altogether 1024 × 768 micro mirrors, which, with 4 × 4 matrix as a unit, could be divided into 256 × 192 units. Different values of reflectivity can be generated by rotating the specific micro mirrors in each unit.

The schematic diagram of 4 × 4 unit patterns at 0%, 12.5%, 25%, 37.5%, 50%, 62.5%, 75%, 87.5% and 100% rotation ratios are shown in Fig. 2. Each micro-mirror state is set by the corresponding binary bitmap that uploading to the upper computer software. When the bitmap is uploaded to the computer software, the binary data will be downloaded to the static random access memory (SRAM) cell, which exists below each micro mirror. The SRAM cell is applied to the address electrodes, creating an electro-static attraction. Each micro mirror then either stays in place or quickly rotates to its opposite state according to the SRAM data. Once stabilized, the micro mirror could be considered electro-mechanically "latched" in its desired position, and the feedback light then will be hold. Thus the angle of micro mirror shown in Fig. 2(a) is determined by the corresponding pixel of uploaded bitmap, which is shown in Fig. 2(b).

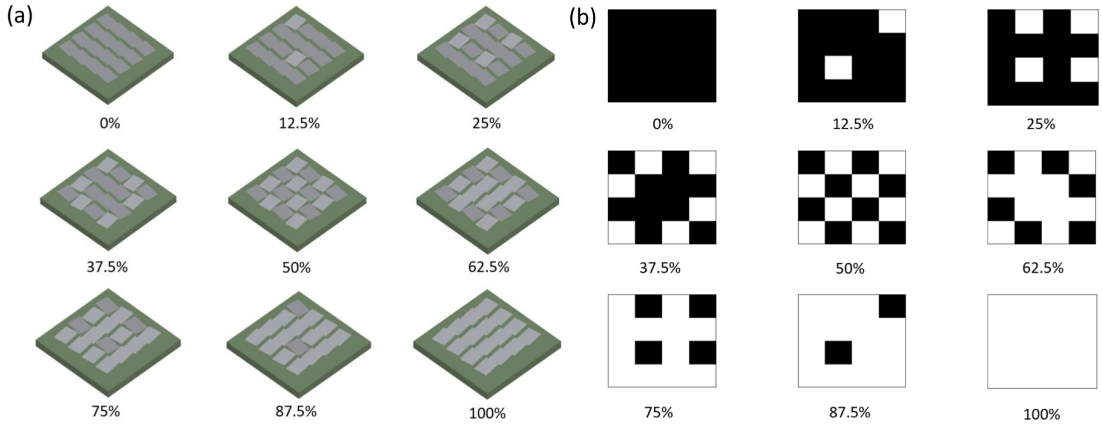

Fig. 2. The schematic diagram of 4 × 4 unit patterns at nine different rotation ratios: (a) micro-mirror state of each unit pattern in DMD, (b) corresponding bitmap of each unit pattern uploaded to the control software.

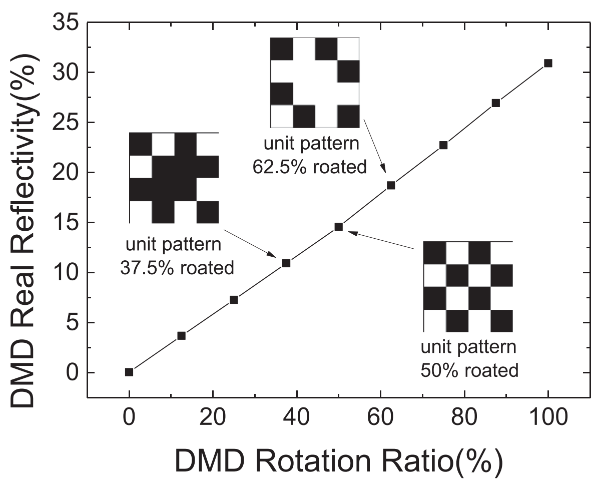

Fig. 3. The calibrated real reflectivity versus the DMD rotation ratios.

Then, we measured the DMD reflectivity for calibration. We measured 9 data points for this experiment, respectively 0%, 12.5%, 25%, 37.5%, 50%, 62.5%, 75%, 87.5% and 100%, which stand for the rotation ratios of "on" state micro mirrors to the total micro mirrors in DMD. The results are shown in Fig. 3, which is obtained by dividing the specific value between the reflected optical intensity at different rotation ratios and the original optical intensity. As it can be seen that the relationship between DMD rotation ratio and real reflectivity has good linearity. However, because there is the gap between DMD micro mirrors and the unsmooth structure formed by micro mirrors rotated, numerous lights will be unreflected or scattered. Thus the real reflectivity could not reach 100%. It could be seen from the Fig. 3 that when the rotation ratio of DMD micro mirrors is 100%, the real reflectivity is only about 31%. But for all this, it could also be seen that with the increase of the rotation ratio, the real reflectivity increases linearly. Three different unit patterns are shown in the inset of Fig. 3. Each unit is composed of a 4 × 4 matrix that can be extended to the whole 1024 × 768 pixels.

Note that when all the DMD units worked, a periodic structure will be formed to become a similar two-dimensional optical grating [15]. At this time, the DMD plays the role of lasing mode selection

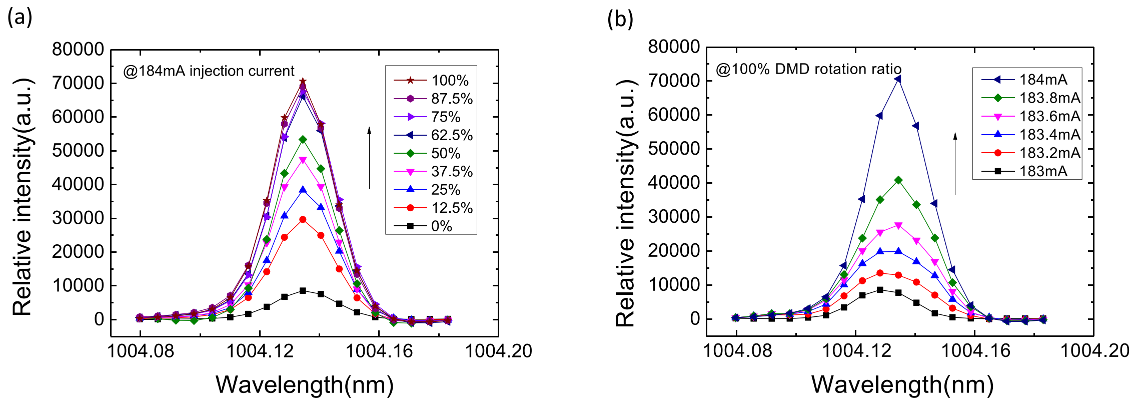

Fig. 4. The comparison of InAs/GaAs QD lasing spectrums in achieving the same single-mode intensity: (a) our method: changing the feedback light of DMD, (b) conventional method: changing the injection current of laser diode.

to output single-mode lasing. The intensity of single-mode lasing can be regulated by setting the rotation ratio of the micro mirrors, since the micro mirrors are controlled by the software of the upper computer.

We constructed the setup as illustrated in Fig. 1. The light emitted from one facet of the InAs/GaAs laser diode is collimated by a lens and the light is reflected back by DMD and fed into the laser diode again. The light emitted from the other facet is collimated as well for optical measurement with a Fourier transform infrared (FTIR) spectrometer (Nicolet 760), installing a high sensitive liquid-nitrogen-cooled InSb detector. The position of lens and DMD are optimized by FTIR to achieve the best light coupling. The InAs/GaAs quantum dot laser diode in Fig. 1 is placed on a gold-plated heat sink, below which is a Peltier thermoelectric cooler so that the temperature of the laser device is controlled at room temperature (20 °C).

The spectrums corresponding to DMD rotation ratios were obtained by setting different unit patterns at the injection current of 184mA. There are 9 data points for this experiment, respectively 0%, 12.5%, 25%, 37.5%, 50%, 62.5%, 75%, 87.5% and 100%. The relation between the intensity of selected single mode and different rotation ration is shown in Fig. 4(a). It could be observed that when the rotation ratio is 0%, i.e., when all the micro mirrors are in "off" state, the spectrum is presented by a free-running laser with no optical feedback. At this time, the single-mode intensity established in the weakest state.

When the micro mirrors are in "on" state, each micro mirror is rotated along its diagonal to form a periodic surface structure on DMD, similar to the two-dimensional reflection grating. With the DMD rotation ratio increasing, the optical feedback is enhanced, so the intensity of single mode increases correspondingly. It could be seen from Fig. 4(a) that the peak wavelength of the selected single mode is about 1004.135 nm in this experiment. As the rotation ratio increases, the feedback of the light is increased gradually. Correspondingly, the single-mode peak increases gradually. Note that when the intensity of the single mode increases, its peak wavelength does not get red shift or blue shift.

However, if we want to achieve the same intensity variation through the current injection method, there will be a wavelength shift. The spectrums of InAs/GaAs QD lasers are illustrated in Fig. 4(b), at different injection currents (183 mA, 183.2 mA, 183.4 mA, 183.6 mA, 183.8 mA and 184 mA). Under the junction temperature effect, there is about 0.006 nm red shift when the injection current increases 1 mA [16]. Obviously, the method of Fig. 4(a) is more stable than the Fig. 4(b) from this comparison. That is principally because the optical feedback hardly affects the junction temperature of the InAs/GaAs QD laser diode [17].

Besides, it also could be observed from Fig. 4(a) that the increase of the single-mode intensity slows down significantly when the rotation ratio exceeds 62.5%. We assume that this is mainly

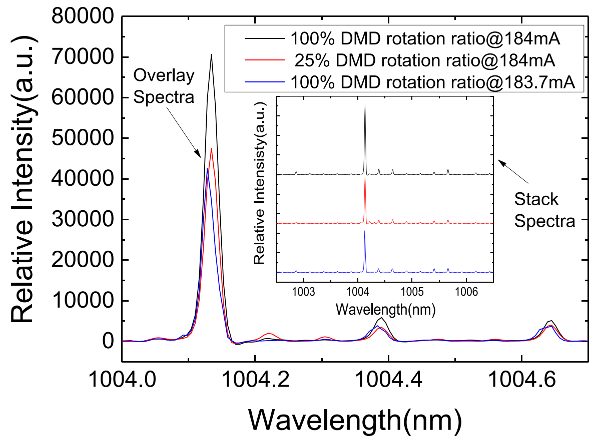

Fig. 5. The comparison of lasing spectra obtained respectively by the conventional method and our method as the power declined to the same level.

caused by the special structure of DMD. With the increase of rotation ratio, the DMD surface tends to be a plane mirror and its periodic grating structure weakens gradually. Thus the performance of the single-mode selection will be weakened [18]. At the same time, the other modes will be strengthened. Nevertheless, when every micro mirror is rotated along its diagonal to the angle of $+12°$, a weakly periodic structure still exists. So the single mode could still be selected but the performance of the single-mode selection declines greatly.

Furthermore, we added experiment results to prove our method maintaining both wavelength unshifted and making compensation to the changed power. Fig. 5 shows the comparison of lasing spectrums obtained respectively by the conventional method and our method when the power was declined to the same level. As it can be seen from Fig. 5, the lasing wavelength obtained by the conventional method (blue curve) has a blue shift, while the lasing wavelength obtained by our method (red curve) is stably consistent with the original wavelength value (black curve). In order to achieve the same power, the conventional method reduced the injection current from 184 mA to 183.7 mA, while our method reduced the DMD rotation ratio from 100% to 25%. A little weaker intensity of the blue single-mode peak than the red single-mode peak appeared in the overlay spectra. We assume that it is due to the energy reserved in other side modes, as it can be seen from the spectra in Fig. 5.

Specially, when the rotation ratio of micro mirrors reaches 50%, the two adjacent micro mirrors are in “on” and “off” state respectively. In that case, the DMD surface achieves the periodic structure with the highest micro-mirror variation density, it should have the most powerful single-mode selection performance; however, there is a stronger optical feedback at the rotation ratio of 62.5% than at 50%. Under the comprehensive effect of DMD periodic structure and optical feedback intensity, the single-mode lasing at 62.5% achieves the highest performance. As it can be proved from the calculation of our measurement, the side mode suppression ratio (SMSR) achieves at the maximum value of 22 dB when the DMD rotation ratio is 62.5% [19].

4. Analysis and Discussion

Furthermore, to prove our viewpoint, spectrums in a wider range (1002 nm–1008 nm) have also been measured, and the spectrums obtained at 9 set rotation ratios are shown in Fig. 6(a). It can be found out that when the rotation ratio exceeds 62.5%, besides the selected mode of wavelength at 1004.135 nm, some other side modes start to rise. The result shows that the DMD's ability to select the single mode begins to weaken. It means that the performance of single-mode selection is diminished as the rotation ratio beyond a certain extent due to the DMD surface approaching the plane mirror surface.

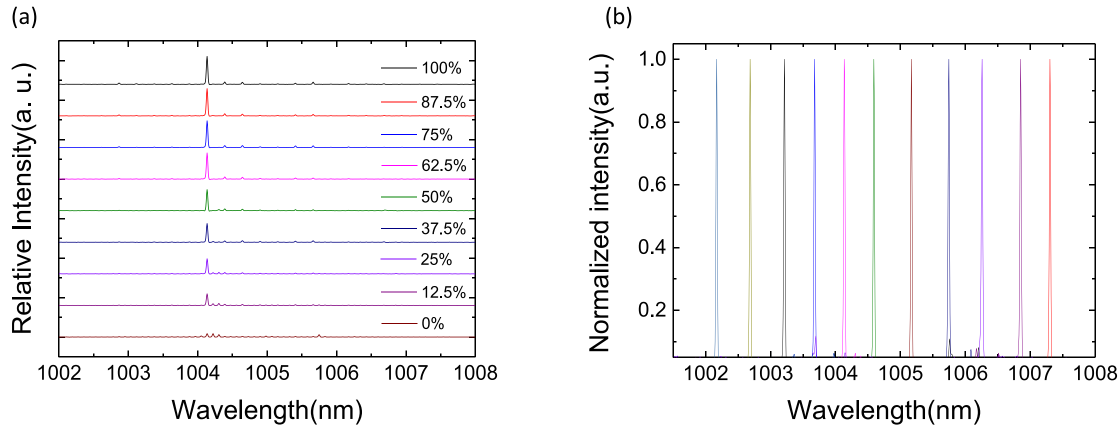

Fig. 6. The spectrums of InAs/GaAs QD laser obtained by our method: (a) regulating the single mode lasing intensity by changing the DMD reflectivity, (b) tuning the lasing wavelength by changing the angular position of DMD.

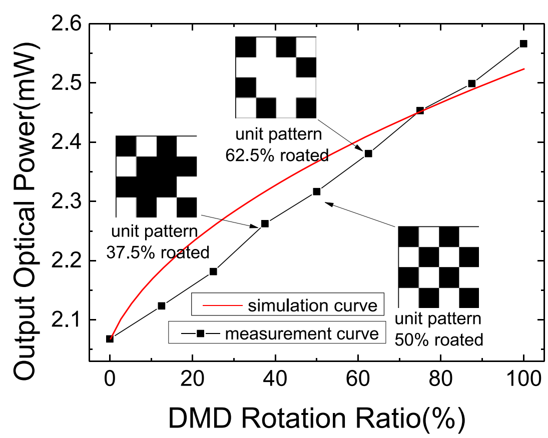

Fig. 7. Dependence of the output optical power with optical feedback on the DMD rotation ratio.

At the same time, by rotating the angular position of DMD, tuning spectrums were obtained when the rotation ratio was 100%. This is because the effect on grating efficiency of having all of the DMD micro mirrors in the on (or the off) state can be achieved by regarding the DMD as a two-dimensional blazed diffraction grating. Nominally the reflectivity of a single DMD pixel follows the reflectance curve of bulk aluminum within the wavelength range from 400 nm to 2500 nm. Thus the DMD is actually a two-dimensional blazed diffraction grating, for which the diffractive behavior in near-infrared wavelengths is evident. The tuning spectrums are shown in Fig. 6(b) with normalized intensity for clarity. A tuning range of about 5 nm has been achieved. This result shows that the DMD could also be applied as a wavelength selector for its special structure.

In addition, we measured the output optical power of the InAs/GaAs laser diode with different optical feedback intensity to testify our assumption. The optical feedback intensity is controlled by the DMD settings. Under continuous wave operation at 20 °C, the laser beam from the front facet of InAs/GaAs quantum dot laser diode is collected by a Melles Griot optical power meter equipped with an integrating sphere Ge detector. Nine output optical power values were recorded under the respectively corresponding DMD rotation ratio settings in 0%, 12.5%, 25%, 37.5%, 50%, 62.5%, 75%, 87.5% and 100%. The relation between the output optical power and the DMD rotation ratio with 9 data points is illustrated in Fig. 7.

In the inset of Fig. 7, three different unit patterns are taken to show the micro-mirror state in each 4×4 matrix (corresponding to Fig. 2). From Fig. 7, it can be seen that with the increase of the DMD rotation ration, i.e., with the DMD reflectivity increasing, the output optical power increases as well. The explanation of this phenomenon can be proved by the Fabry-Perot cavity equations. Back to Eq. (1), we could substitute r_{eff} for r_2 to study the dependence between output optical power P and equivalent reflection coefficient r_{eff}, resulting in the following equation [20]:

$$\frac{P_0}{P} = \left(\frac{R_1}{R_{eff}}\right)^{1/2} \left(\frac{1 - R_{eff}}{1 - R_1}\right) = \left(\frac{|r_1|^2}{|r_{eff}|^2}\right)^{1/2} \left(\frac{1 - |r_{eff}|^2}{1 - |r_1|^2}\right) \tag{4}$$

Where P_0 is the initial laser power, r_1 and R_1 are the reflection coefficient and reflectivity of the cleaved facet. The resulting Eq. (4) defines the dependence of P on r_{eff}. By adjusting the reflectivity of DMD, the r_{eff} can be varied according to Eq. (1). For each value of r_{eff}, P can be measured. On the other hand, many pairs of (P, R_{d}) can be obtained by the simulation software Matlab. The comparison between simulation result (red curve) and measurement result (black curve) are shown in Fig. 7.

The measured relation between the DMD rotation ratio and output optical power shown in Fig. 7 agrees well with the simulation result. Basically consistent with the linear variation in Fig. 3, the total output optical power nearly equals to the sum of the output optical power emitted from the cleaved facet and the optical feedback power from DMD, indicating that the total energy is conserved. It is further proved that the reason of the selected single mode increase speed slowing down is due to the energy of the feedback light transferred to several other side modes, which agrees the viewpoint proposed by us previously.

5. Summary

In summary, we have demonstrated a new method to regulate the single-mode lasing of InAs/GaAs QD laser diode. In this method, the key optical component is a DMD mirror, which is used to vary the external optical feedback. The single-mode lasing is generated by the special structure of DMD, which can be taken as a two-dimensional grating. From the above experiments, we discovered the phenomenon of DMD regulating laser spectrums and observed the changing rule of the single-mode peak. We assume that the change rule of selected single-mode peak is the comprehensive result of the DMD special structure and the optical feedback. We find out the single-mode selection performance of DMD begins to weaken when the DMD rotation ratio exceeds 50%. That is because the energy of selected single mode is transferred to other side modes. In addition, we measured wider range spectrums of InAs/GaAs quantum dot laser diode and conducted the output optical power versus DMD settings experiment to verify our conclusion.

The advantage of our method is regulating the single-mode lasing intensity without wavelength shift, which is intrinsically different from the conventional method. Moreover, the lasing wavelength could be tuned by rotating the DMD. Particularly, the DMD pattern is controlled by the digital computer, which could be modulated by various external signals. To get higher regulation accuracy, it only needs to set a more precise unit pattern (i.e., increase the numbers of micro mirrors in a unit) or to form a larger light spot with beam expanders. In summary, this method is a much available way in regulating the output single mode of semiconductor lasers. Meanwhile, its simply structure and rapidly digital regulation is of great significance for it could provide an effective method for future applications.

Acknowledgement

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