

Article

Optical Bistability and Thermal Mode Hopping in External Cavity Feedback Semiconductor Lasers

Da Meng^{1,2} , Haiyang Yu,¹ Yejin Zhang^{1,2} and Jianguo Liu^{1,2,*}

¹ Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China;

² University of Chinese Academy of Sciences, Beijing 100049, China

* Correspondence: jgliu@semi.ac.cn

Abstract: The external cavity feedback semiconductor laser shows obvious optical bistability in practice. That is, at the same operating temperature, different temperature tuning directions will lead to different laser mode outputs. This will lead to optical mode hopping and unstable output wavelength of the laser. In this work, we measured this phenomenon and explained it through a theoretical model with thermal synchronization considered. Our measured results show obvious bistability and temperature tuning direction dependence. In order to explain this phenomenon, we considered the physical characteristics of each optoelectronic component in the external cavity, founded that the temperature changes of each component were not synchronized over time. After establishing a model by considering this thermal asynchrony phenomenon, we have well explained this phenomenon.

Keywords: Optical Bistability; Thermal Mode Hopping; Semiconductor Lasers

1. Introduction

External cavity feedback is a common laser linewidth narrowing scheme. At present, a lot of work has been done to narrow the linewidth through the external cavity. The external cavity scheme is mainly based on Littrow or Littman structure [1,2]. Considering the volume of blazed grating and other issues, more Littrow-like or Littman-like structures based on non-blazed grating form appear. The core of each scheme is to screen and lock the optical frequency in the external cavity, and then suppress the edge mode noise, so as to narrow the laser linewidth. In addition to the blazed grating, many excellent works have successively developed more other devices to meet the requirements of the scheme, including Bragg volume grating [3–5], Fabry-Perot etalon (FP) [6], fiber grating [7,8], planar lightwave circuit (PLC) [9–11] and quantum dot lasers [12,13], etc. And many of them have been applied to engineering practice.

After the continuous advancement of applications, especially after the integration of lasers, the external cavity feedback semiconductor laser has obvious bistability, including optical longitudinal mode bistability [14–17] and optical transverse mode (polarization) bistability [18,19]. This phenomenon causes laser mode hopping during disturbances, which can affect the stability of laser output. In addition to bistability, lasers also exhibit other dynamic characteristics, such as stable fixed points [20,21], quasi periodic [22,23], chaos [24,25], etc. These characteristics will also affect the mode hopping behavior of the laser. The research on mode hopping of external cavity semiconductor lasers is mainly divided into two aspects: experimental measurement and theoretical analysis. Experimental measurement [26,27] is mainly focused on finding novel and reliable measurement methods of mode hopping. The main ideas of theoretical analysis [28,29] are focused on discussing and analyzing the output advantages of several competitive models. However, in the literature we know, there has been no discussion of directly correlating bistability with thermal synchronization problem.

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In this work, we chose a general configuration to build our integrated external cavity narrow linewidth semiconductor laser. Based on the laser, we measured that the experimental results have optical bistability and time inversion asymmetry. This result is also consistent with the measurement results of commercial devices of similar schemes. It has strong reproducibility. In order to understand this phenomenon, we first simulated a model results with perfect time inversion symmetry as a reference. Then we found and explained the origin of this thermal tuning asymmetry based on the device characteristics. Finally, By taking into account the factors we discovered in our model, we have well explained this phenomenon.

2. Configuration and Methods

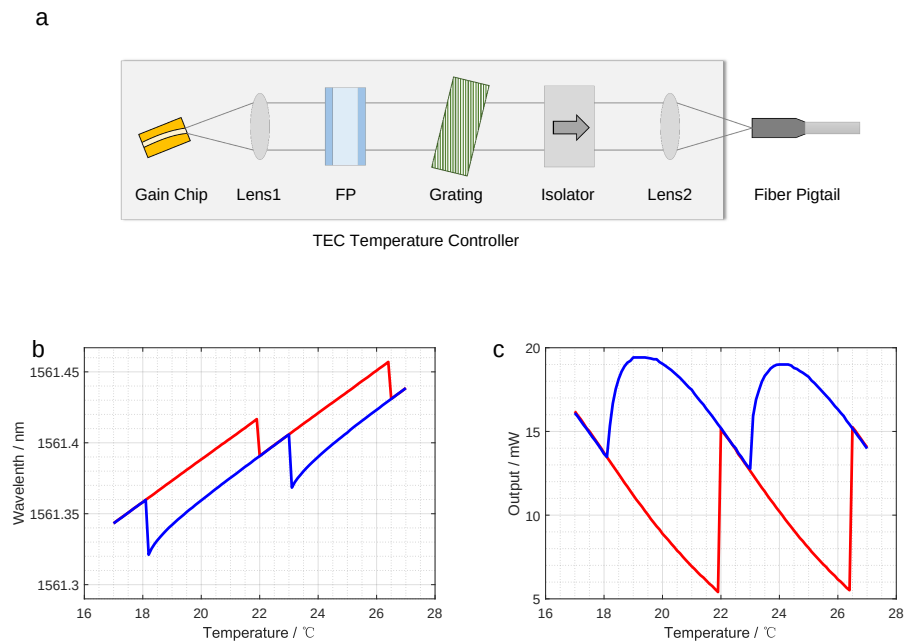


Figure 1. a. Configuration of the semiconductor laser in this work; b. Laser output wavelength curves changing with temperature, under temperature tuning; c. Laser output power curves changing with temperature, under temperature tuning. In b and c, the solid red line is the temperature tuning curve in the heating direction, and the solid blue line is in the cooling direction. The ambient temperature for the experiment is 25 °C and all components are sealed in a tube shell filled with nitrogen.

The schematic diagram of a typical external cavity feedback semiconductor laser (ECL) is shown in Figure 1a. The laser consists of a gain chip, a Fabry-Perot Etalons (FP), a volume Bragg grating, an isolator, two lenses and a thermo electric cooling (TEC) temperature controller. The gain chip provides gain for laser oscillation. One end of the gain chip has high reflectivity and the other end has high transmissivity. The high reflectivity end acts as the mirror of the external cavity to reflect light, and the other end with high transmissivity faces the interior of the cavity to facilitate the entrance and exit of the resonant light. FP can purify resonance light and select longitudinal mode. The bandwidth of FP is 7.5 GHz in this paper. The filter bandwidth of volume Bragg grating is 125GHz, which acts as the cavity mirror at the output side of the external cavity and can purify the longitudinal mode of the output light. The isolator ensures the isolation of the external cavity of the laser from the outside. The lens 1 plays the role of beam expansion, so that the small aperture beam inside the gain chip can be coupled with the external cavity, and the lens 2 shapes the output beam and couples it into the fiber tail pipe. TEC temperature controller is used to keep the temperature of the plane constant, where the whole cavity is located, especially in the

area near the gain chip. The entire external cavity is assembled on a substrate, and the TEC temperature controller controls the substrate temperature, so as to keep the temperature of the entire external cavity constant, especially the area near the gain chip.

The external cavity filters laser's frequency in the form of an optical comb, and its equivalent length determines the frequency of a single longitudinal mode and the interval between each longitudinal mode. The equivalent length L_{eq} of the external cavity is defined as the sum of the product of the refractive index n_k and length of each segment L_k in the cavity.

$$L_{eq} = \sum_{k=1,2,3,\dots} L_k n_k \quad (1)$$

The summation section includes the gain chip, lens, FP, and the gas components between each component.

In the optical comb, the integral N times of each wavelength λ_N must be the same as the equivalent cavity length, so the equivalent cavity length can also be written as

$$L_{eq} = N\lambda_N. \quad (2)$$

Conversely, the longitudinal mode wavelength λ_{comb} corresponding to the comb near a certain wavelength λ_{given} can be solved as follows

$$\lambda_{comb} = L_{eq} / \text{round}\left(\frac{L_{eq}}{\lambda_{given}}\right), \quad (3)$$

where the operator $\text{round}()$ represents rounding.

According to eq. (2), for a given longitudinal mode wavelength λ_{comb} , the wavelength interval $\Delta\lambda_{comb}$ of the comb can be obtain by

$$\Delta\lambda_{comb} = \frac{\lambda_{comb}^2}{L_{eq} - \lambda_{comb}}. \quad (4)$$

Therefore, the function of the optical comb near λ_{comb} can be written as

$$F_{eq}(\lambda) = \sum_{k=0,\pm 1,\pm 2,\dots} \delta[\lambda - \lambda_{comb} + k\Delta\lambda_{comb}]. \quad (5)$$

λ is a variable, representing the wavelength. $\delta[]$ is unit pulse sequence in discrete domain,

$$\delta[x] = \begin{cases} 1, & x = 0 \\ 0, & x \neq 0 \end{cases}. \quad (6)$$

In practice, it is not easy to calculate the equivalent external cavity length by e.q.(1), but the frequency interval at the specified frequency can be measured. According to e.q.(4) for a given longitudinal mode wavelength λ_{comb} and a given wavelength interval $\Delta\lambda_{comb}$ of the comb, the equivalent cavity length can also be written as

$$L_{eq} = \frac{\lambda_{comb}(\lambda_{comb} + \Delta\lambda_{comb})}{\Delta\lambda_{comb}}. \quad (7)$$

Through the above equations and experimental results in Figure 1b, we can simulate the optical comb and obtain all its properties. It turns out that the optical comb redshifts with the increase of temperature.

FP filtering selects the longitudinal mode in the external cavity through its narrow filtering bandwidth. Similar to the external cavity, the central wavelength of FP's filtering bandwidth is related to its equivalent length $L_{FP}n_{FP}$, in witch L_{FP} is the actual length of FP, and n_{FP} is the refractive index of FP. They both are temperature related. Because the temperature range involved in this work is narrow, it can be considered that the

refractive index and actual length meet the linear relationship with temperature in this range. Therefore, they can be simply expressed as linear functions of temperature T.

$$L_{FP} = L_{FP0}(1 + a_{qz}(T - T_0)) \quad (8)$$

$$n_{FP} = n_{FP0} + \frac{\Delta n}{\Delta T_{qz}} (T - T_0) \quad (9)$$

The a_{qz} is the linear thermal expansion coefficient of quartz, in the order of 10^{-7} [30]. The $\frac{\Delta n}{\Delta T_{qz}}$ is the refractive index temperature coefficient of quartz, which is negative and in the order of 10^{-5} [31]. The central wavelength frequency λ_{FP} of FP filtering bandwidth near a given wavelength λ_{given} can be calculated by L_{FP} and n_{FP} .

$$\lambda_{FP} = L_{FP}(T)n_{FP}(T)/\text{round}\left(\frac{L_{FP}(T)n_{FP}(T)}{\lambda_{given}}\right) \quad (10)$$

As $|\frac{\Delta n}{\Delta T_{qz}}|$ is much larger than $|a_{qz}|$, the negative drift of refractive index dominates the drift of FP central wavelength, which makes the FP central wavelength λ_{FP} blue shift with temperature increasing.

Since the filtering bandwidth of FP is much larger than the linewidth of each longitudinal mode in the comb, the shape of FP filtering curve also needs to be considered. In general, the passband filtering curve of FP meets the Lorentz distribution, that is

$$F_{FP}(\lambda) = \frac{(\tau_{FP}\pi)}{\pi} \frac{\tau_{FP}}{(\lambda - \lambda_{FP})^2 + (\tau_{FP})^2}. \quad (11)$$

λ is a variable, representing the wavelength. τ_{FP} represents the filtering bandwidth of FP and is also the FWHM of the Lorentz distribution. In this work, $\tau_{FP} = 7.5\text{GHz}$. The first numerator $(\tau_{FP}\pi)$ on the right of the equal sign is a normalization coefficient, which guarantees the maximum value of this curve is 1.

The grating is similar to FP, but has a much wider filtering bandwidth of 125GHz , so the passband filtering function of the grating is directly given here:

$$F_{grt}(\lambda) = \frac{(\tau_{grt}\pi)}{\pi} \frac{\tau_{grt}}{(\lambda - \lambda_{grt})^2 + (\tau_{grt})^2}. \quad (12)$$

λ is a variable, representing the wavelength. τ_{grt} represents the filtering bandwidth of grating and is also the FWHM of the Lorentz distribution. The center wavelength of grating $\lambda_{grt} \approx \lambda_{FP}$. The first numerator $(\tau_{grt}\pi)$ on the right of the equal sign is a normalization coefficient, which guarantees the maximum value of this curve is 1.

The wavelength selectivity of the laser in this work is composed of external cavity comb, FP and grating. The gain of the optical gain chip can be considered flat in a small wavelength range. So, only considering the static process, the longitudinal mode with the lowest loss can always obtain a competitive advantage and output. For the laser in this work, the normalized comprehensive loss function is

$$F_{com}(\lambda) = F_{eq}(\lambda)F_{FP}(\lambda)F_{grt}(\lambda). \quad (13)$$

In discussing the competition of modes in the early stage of resonance, the above equation derives the screening losses of different modes. In addition to this, the so-called Bogatov effect [32] needs to be taken into account in the calculation. Due to nonlinear effects such as four-wave mixing, adjacent short-wavelength modes provide additional

gain for long-wavelength modes when multiple modes coexist. [33] According to the model of Lenstra et al., the Bogatov dynamic gain can be written as

$$g_{Bogatov} = \frac{1}{4} \frac{\theta_{short}(g_{long} + g_{short})(\alpha_{short}\Delta\omega - \frac{1}{T_{long}} - \theta_{short}P_{short})}{\Delta\omega^2 + (\frac{1}{T_{long}} + \theta_{short}P_{short})} P_{short} \cdot [33] \quad (14)$$

θ_{short} is gain coefficient of the short-wavelength mode. g_{short} and g_{long} are linear gain for short-wavelength and long-wave modes respectively. α_{short} is linewidth parameter of the short-wavelength mode. T_{long} is lifetime of long-wave modes. $\Delta\omega$ is angular mode-frequency difference between the short-wavelength and long-wave modes. In this work, $\Delta\omega$ is taken as $2\pi \times 3.5\text{GHz}$, and the remaining parameters will follow the original model. P_{short} is the power of the short-wavelength mode. Taking into account the Bogatov effect, the output power P_{out} rate equation corresponding to the external cavity feedback is

$$\frac{dP_{out}}{dt} = R - (\gamma - g)P_{out} + \theta N_0 P_{out} + g_{Bogatov} P_{out} \cdot [33] \quad (15)$$

t is time. R is spontaneous emission rate. γ is cavity loss rate. g is linear gain. θ is differential gain coefficient. N_0 is the average inversion available for lasing. This work discusses the competition of modes before lasing. At this point, R and N_0 can be considered very small. Therefore, e.q. (15) can be simplified as

$$\frac{dP}{dt} = (g - \gamma)P + g_{Bogatov}P. \quad (16)$$

Linear gain g is provided by the gain chip. Within a smaller range, the linear gain can be considered flat. Cavity loss rate γ can be calculated by e.q. (13). The time of mode establishment is very short. (It is generally on the order of 10^{-8} [33,34]). For ease of processing, in this work, the mode establishment time is taken as $t_{establishment} = 5\text{ns}$, and $g_{Bogatov}$ is simply integrated with $t_{establishment}$. The result of the integration is used as Bogatov gain during each round of mode establishment. This method can effectively preserve the positive correlation between gain and short wavelength mode power, and simplify the calculation.

Figure 1b and c show the experimental measurement data. The pump current of the laser is kept at 160 mA. The temperature is controlled by TEC, and the temperature value is measured by a thermistor attached to the optical gain chip. After each temperature adjustment, the data measurement record will wait until the laser is completely stable. The laser output optical wavelength is measured by a Yokogawa AQ6151B wavelength meter. The laser output power is measured by a Thorlab S146C photodetector, and read by a Thorlab PM100D console.

3. Result and Discussion

The equivalent length of the external cavity changes with the substrate temperature changing, which leads to the drift of the longitudinal mode wavelength. Therefore, the laser wavelength can be tuned in a small range by changing the control temperature of the substrate. In this process, we observed that the direction of temperature tuning affects the output longitudinal mode of the laser, as shown in Figure 1b and c. Figure 1b shows the corresponding relationship between laser output wavelength and temperature. Figure 1c shows the corresponding relationship between laser output power and temperature. In these two figures, the curves of different colors correspond to different temperature changing directions. The blue line represents the cooling process, and the red line represents the heating process. Each data point is a steady-state result measured after reaching the thermal equilibrium. One interesting point is that at the same temperature, the difference between heating and cooling process will lead to different output modes. And the two longitudinal modes can both output stably. It means the laser resonator is bistable. Another

interesting point is that in the data of the heating process, the longer wavelength mode with lower output power will be more competitive and stable than the shorter wavelength mode with higher output power. In addition, it can be observed that during the cooling process, when the output power of the laser reaches its maximum, there appears a power saturation zone. And after going through the saturation zone, the power drops rapidly and mode hopping occurs.

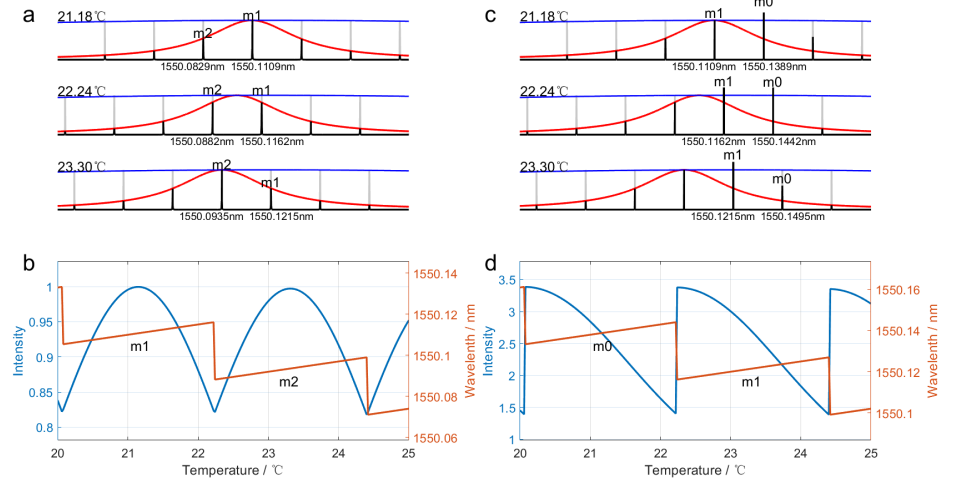


Figure 2. a. The filtering curve steady-state distribution of each device in the external cavity at three typical temperature control points. The comb-like light gray curve corresponds to the optical comb; The Lorentz-shaped red curve corresponds to the FP; The blue curve represents the grating; The comb-shaped black curve corresponds to the product of the previous three curves. b. Temperature tuning simulation results with time inversion symmetry. c. The result of considering the Bogatov effect [32] on the basis of fig a. d. Temperature tuning simulation results with time inversion symmetry and Bogatov effect [32]. The modes m0, m1 and m2 are three adjacent modes, with wavelength $\lambda_{m0} > \lambda_{m1} > \lambda_{m2}$. The wavelength interval is taken as 0.028 nm (≈ 3.5 GHz).

Using the e.q. (13), we can simulate the relationship between the laser output mode and temperature. For convenience, the central wavelength is set as 1550 nm, which will not affect the presentation of simulation results. Since the relevant derivation does not contain time related variables, the content of the analytical model is time inversion symmetric. It means any operations can be canceled by their reverse operation. For three typical temperatures, the distribution of each curve is shown in 2a. The comb-like light gray curve corresponds to the optical comb curve, which is obtained from the external cavity equation of e.q. (5). The Lorentz-shaped red curve corresponds to the curve of FP, which is obtained from the FP equation of e.q. (11). The blue curve represents the grating curve obtained from the grating equation of e.q. (12). It is also a Lorentz-shaped curve, but it is close to a straight line in the figure, because its FWHM is far greater than the FP curve. The comb-shaped black curve with various intensities corresponds to the product of the previous three curves, which is obtained from e.q. (13). As showed in Figure 2a, at 21.18 °C, the attenuation of m1 mode is the lowest, it gets competitive advantage and outputs. With the increase of temperature, the curve of FP and grating shifts blue, and the comb shifts red. The wavelength of m1 mode becomes larger, and the attenuation also increases. When the temperature reaches 22.24 °C, the attenuation of m2 mode is lower than m1 mode for the first time, and m2 mode gains competitive advantage. Then mode hopping occurs, the wavelength of m2 mode starts to output. With temperature keeping increasing, the wavelength of m2 mode becomes larger. And its intensity also gradually increases with attenuation decreasing. At 23.30°C, the attenuation of m2 mode becomes the lowest, and its intensity reaches the largest. This process is vice versa. And the bistability will

only occur when the attenuation of the two modes is close, such as the case near 22.4 °C in Figure 2a. This is because the above system is time reversal symmetry. However, the characteristics revealed by the experimental data can not be possessed by a time reversal symmetry system. As a result, this physical model with time inversion symmetry can only get the temperature tuning curve as shown in Figure 2b. The heating and cooling processes are consistent. This is inconsistent with the experimental data.

After considering the Bogatov effect, the long-wavelength mode gains a significant advantage in mode competition. Figure 2c shows this feature. The m_0 mode in Figure 2c does not originally have a competitive advantage due to FP filtering. But with the help of the Bogatov effect, m_0 mode can achieve higher intensity than the m_1 mode, and obtain output in mode competition. Therefore, the Bogatov effect causes the temperature tuning curve of the laser to exhibit significant asymmetry, as shown in Figure 2d. In Figures 1b and c, the temperature tuning curve of the laser is always dominated by the long wavelength mode. The introduction of the Bogatov effect explains this characteristic well. The shape of the curve in Figure 2d is also similar to the real tuning curve. However, the tuning curve here is still insensitive to the tuning direction. Every temperature tuning is accompanied by a change in cavity length. It corresponds to the process of original mode mismatch and new mode re-establishment. After the dissonance of the cavity, the previously competitive mode was reshuffled. As long as the initial conditions are consistent, the output of the pattern is always consistent, independent of the path that reaches the initial conditions. That is to say, after considering the Bogatov effect, although the symmetry of the mode gain is broken, the equation is still time reversal symmetric. In order to obtain the experimental results, there must be some other mechanisms that introduce time reversal asymmetry.

Consider about time. The above deduction implies a assumption that various operations occur at the same time. For example, it is implicitly assumed that the red shift of the external cavity comb and the blue shift of the FP curve occur simultaneously and work together. In fact, due to the difference of electron transition time and thermal conduction time, the operations of each part are not synchronous. In order to explain the difference, we carried out several thermal simulations of the external cavity structure components.

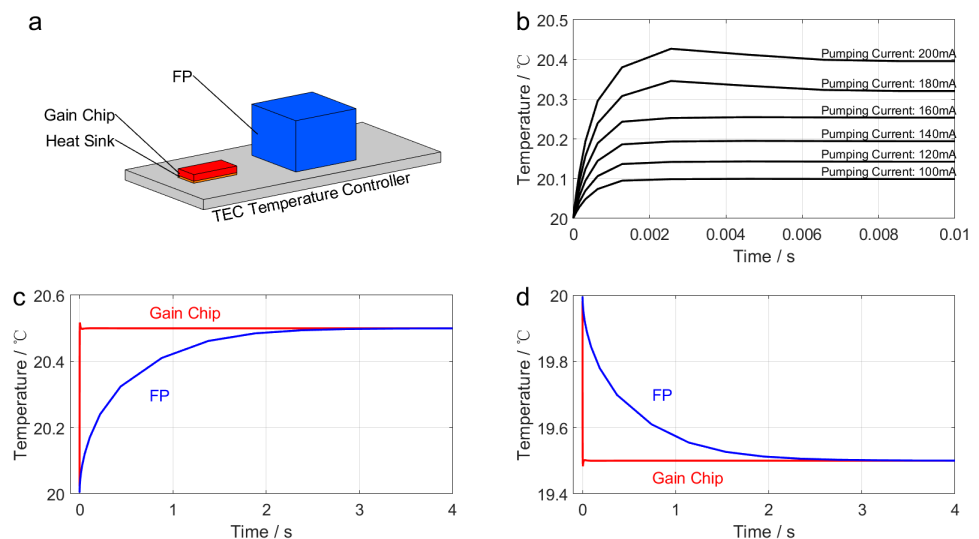


Figure 3. a. The schematic diagram of thermal simulation structure; b. Chip active working temperature rising simulation result; c. Devices passive heating simulation result; d. Devices passive cooling simulation result.

The schematic diagram of thermal simulation structure is shown in Figure 3a. It is assumed that the upper surface of the temperature controller always maintains a constant temperature and has good thermal contact with the lower surface of each device. And

adiabatic approximation is made for other surfaces of all devices. We simulated three scenarios, including a chip active working temperature rising simulation (Figure 3b) and devices passive heating (Figure 3c) and cooling (Figure 3d) simulations. In Figure 3b, The gain chip is considered as a constant power heat source, and different pump currents represent different heating power. It can be found that the thermal stability time of the gain chip is in the order of 10^{-3} seconds under conventional pump current injection. In Figures 3c and d, the gain chip and FP are passively heated and cooled. In these processes, the thermal balance time of the gain chip is still in the order of 10^{-3} seconds, while the thermal balance time of the FP is as long as 3 seconds approximately. Due to the difference of thermal balance time order of magnitude, the temperature change process of gain chip is almost instantaneous compared with that of FP. The temperature change of the gain chip plays a dominant role in the frequency drift of the external cavity comb, while the temperature change of the FP leads to the frequency drift of its passband curve. Therefore, during each temperature change process, the frequency drift of the external cavity optical comb always precedes the frequency drift of the FP passband filtering curve. The grating is similar to FP. In addition, the average lifetime of the upper level in an excited atom is in the order of 10^{-8} seconds [34], which is much shorter than the time required for thermal equilibrium. Therefore, for each process of temperature change, the laser interior will experience three processes with obvious sequence. That is, after the longitudinal mode is established, the optical comb is just starting its shift. And after the optical comb finishing its shift, the FP and grating curves are still slowly continueing their movement process. The time sequence of these three processes is fixed, independent of the direction of heating or cooling. This means that heating and cooling are not mutually inverse processes. These strict three-step process sequences breaks the symmetry of time inversion.

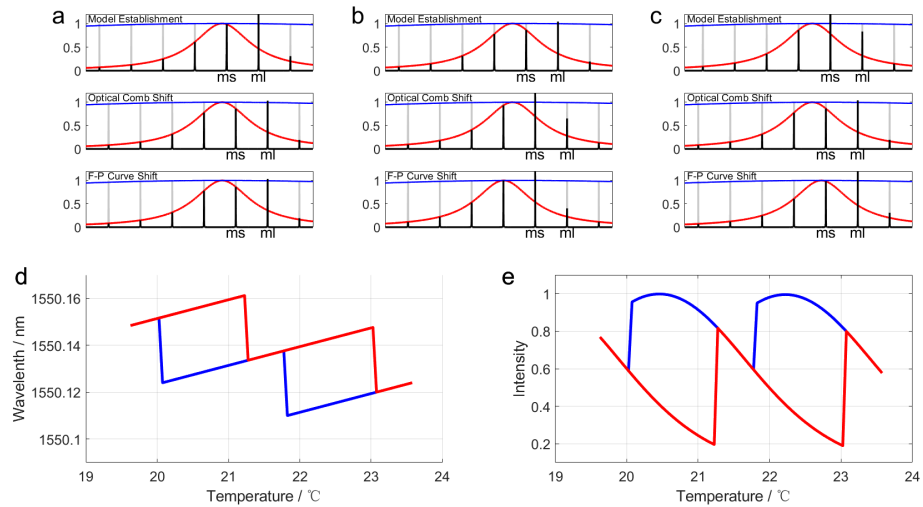


Figure 4. a. Output process of longitudinal mode after power on; b. Mode hopping process of laser when temperature rises; c. Mode hopping process of laser when temperature reduces; d. Simulated curve of laser output wavelength changing with temperature, under temperature tuning; e. Simulated curve of laser output relative intensity changing with temperature, under temperature tuning.

For convenience, in this work, these three-step process sequences will be called *mode establishment*, *optical comb shift* and *F-P curve shift* respectively. Figure 4a, b and c shows three typical processes including this three-step sequence. Figure 4a shows the output process of longitudinal mode after power on. During the *mode establishment* process, thanks to the Bogatov effect, the long-wavelength mode *ml* obtained higher gain than the short-wavelength mode *ms*, which obtained the advantage in the competition and resonant output. Then during *optical comb shift* process, the optical comb red-shifts, the process of mode mismatch and re-establishment remain occurring. Although the transmissivity of

long-wavelength mode ml is lower than that of short-wavelength ms mode, thanks to the Bogatov effect, the long-wavelength mode can still maintain its competitive advantage and obtain output. During the *F-P curve shift* process, since the temperature of FP has not changed, the state of this process is consistent with the previous process. This is similar to the process with Bogatov effect considered in Figure 2c. This indicates that long-wavelength mode ml is always easier to obtain resonant output than short-wavelength mode ms .

Figure 4b shows the mode hopping process of laser when temperature rises. During the *mode establishment* process, with the help of Bogatov effect, the laser maintains the initial state of the long-wavelength mode ml output, even under the conditions of low transmittance. Then during *optical comb shift* process, the optical comb red-shifts, the transmission of long-wavelength mode ml become low enough and unable to maintain competitive advantage. Therefore, the short-wavelength mode ms , which has a very high transmittance and Bogatov gain at this time, obtains the competitive advantage and resonant output. And laser mode hopping occurs. During the *F-P curve shift* process, the FP curve blue-shifts. It further guarantees the side-mode suppression ratio suppression ratio of the short-wavelength mode ms . There is one more thing that needs to be explained here. The *optical comb shift* process is accompanied by mismatch and re-establishment of modes, which is a prerequisite for the occurrence of mode hopping. However, during this process, the filtering conditions of FP have not changed in time. The laser is in a state where mode hopping is less likely to occur. Therefore, Lasers require higher tuning temperatures for mode hopping to occur. Here the tuning direction has an impact on the tuning results.

Figure 4c shows the mode hopping process of laser when temperature reduces. During the *mode establishment* process, the laser maintains the initial state of the short-wavelength mode ms output. Then during optical comb shift process, the optical comb blue-shifts, the transmission of short-wavelength mode ms become lower and the transmission of long-wavelength mode ml become higher. Different from the temperature rise mode hopping process, the dominant mode ms is in the gain saturation state at this time, which cannot effectively inhibit the gain rise of other modes. Therefore, due to its high transmittance and higher Bogatov gain, the long-wavelength mode ml is able to dominate mode competition and output. The laser mode hopping occurs. During the *F-P curve shift* process, the FP curve red-shifts. It further reduces the transmissivity of short-wavelength mode ms And help the long-wavelength mode ml get advantages. This shows that the shortwave mode is difficult to maintain its competitive advantage under the condition of gain saturation.

Through the above analysis, we can find that there are significant differences between the heating and cooling processes of lasers. The Bogatov effect always gives long wavelength modes an advantage in mode competition. This results in an asymmetric shape in the temperature tuning curve. The three-step process sequences allows the tuning direction to affect the tuning result. This causes inconsistency in the heating and cooling tuning curves of our laser. Based on this model, we recalculate the curves of laser tuning wavelength and tuning power respectively. The mode intensity is still calculated using the filtering curve and Bogatov effect, and the mode with the highest intensity is taken as the output mode. The results are shown in Figure 4d and e. It can be found that the simulation results clearly captures the features of the experimental observation shown in Figure 1b and c. There are slight differences in wavelength values between simulation and experimental data. This is because there is a slight deviation between the actual refractive index of each medium and the simulated ones. There are also slight differences between the simulation and experimental data of laser output intensity, as the model does not take into account factors such as laser coupling efficiency. However, even without considering these factors, the trend of the simulation results is very consistent with the experimental data. This model is a good indication of the physical nature of laser's tuning characteristics. It is the characteristics of optical components and thermal asynchrony that together lead to the experimental results in 1b and c. This ultimately causes the tuning characteristics of the laser to exhibit significant bistability and tuning direction dependence.

4. Conclusions

In this work, the phenomenon of bistability in an external cavity narrow linewidth semiconductor laser based on FP and Bragg grating has been measured. Equations with inversion symmetry cannot explain our experimental phenomena well. Through the thermal simulation of different devices, we found that the thermal equilibrium time of each device was significantly different. This thermal asynchrony will result in significant differences in the tuning response speed of different devices. This difference is so significant that it is an order of magnitude difference. Therefore, it leads to a fixed time sequence in the response of each device to thermal tuning. After adding it to our model, the simulation results are in good agreement with the experimental data. It indicates that this discovery well explains the essential physical origin of bistability.

In general, the difference in response time leads to the formation of a fixed tuning response sequence for each device, which causes asymmetry between the hot tuning and cold tuning processes. This asymmetry leads to significant thermal tuning bistability of our external cavity feedback semiconductor lasers. This discovery will help us better understand the nature of tuned bistability and provided a good theoretical guidance for engineering application.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

FP Fabry-Perot Etalons
TEC Thermo Electric Cooling

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