A power and wavelength detuning-dependent hysteresis loop in a single mode Fabry–Pérot laser diode*

Wu Jian-Wei(吴建伟)[a)b)c)†] and Bikash Nakarmi[d)]

[a)] Chongqing Key Laboratory of Optoelectronic Functional Material, Chongqing Normal University, Chongqing 400047, China
[b)] State Key Laboratory of Millimeter Waves, Nanjing 210096, China
[c)] Department of Electrical Engineering, Korea Advanced Institute of Science and Technology, Daejeon 305-714, Republic of Korea
[d)] Department of Information and Communication Engineering, Korea Advanced Institute of Science and Technology, Daejeon 305-714, Republic of Korea

(Received 3 December 2012; revised manuscript received 7 January 2013)

In this paper, we observe experimentally the optical bistability induced by the side-mode injection power and wavelength detuning in a single mode Fabry–Pérot laser diode (SMFP-LD). Results show that the bistability characteristics of the dominant and injected modes are strongly dependent on the injected input optical power and wavelength detuning in an SMFP-LD. We observe three types of hysteresis loops: counterclockwise, clockwise, and butterfly hysteresis with various loop widths. In the case of a bistability loop caused by injection power, the transition from counterclockwise to clockwise in the hysteresis direction with the wavelength detuning from 0.028 nm to 0.112 nm is observed in a way of butterfly hysteresis for the dominant mode by increasing the wavelength detuning. The width of hysteresis loop, induced by wavelength detuning is also changed while the injection power is enhanced from −7 dBm to −5 dBm.

Keywords: single mode Fabry–Pérot laser diode, injection locking behavior, optical bistability

PACS: 42.55.Px, 42.60.Fc, 42.65.Pc **DOI:** 10.1088/1674-1056/22/8/084204

1. Introduction

Optical bistability has attracted much attention in view of the potential applications in optical switching,[1] logic functions,[2] modulation,[3] all-optical 2R regeneration,[4] comparator,[5] and memory,[6] which refers to the situation where two stable output states are associated with a single input state.[7–11] In these technologies, semiconductor materials with strong nonlinear optical properties should be preferentially selected to produce the optical bistability phenomenon. To date, semiconductor-based lasers,[4,5,12,13] amplification,[14,15] and resonators[16,17] have been successfully explored and demonstrated for achieving optical bistability characteristics. In recent years, the single mode Fabry–Pérot laser diode (SMFP-LD) as a novel configuration that is fabricated by a multi-mode FP-LD employing a built-in external cavity has been thoroughly studied by our research group.[18] Compared with the multi-mode FP-LD,[19] the SMFP-LD has unique advantages including a wide tuning range, the self-locking phenomenon, and a high side-mode suppression ratio (SMSR), which can improve some potential parameters like power efficiency, cost effectiveness, and configuration simplicity, and has some significant optical properties and applications,[20–23] in which optical bistability as a very important behavior has already been proposed and demonstrated in the flip–flop function.[24] Of course, as is well known, the structure of Fabry–Pérot laser chip is very similar to that of a Fabry–Pérot laser amplifier (FP-LA), so that the observed optical bistability in an FP-LA is still exhibited on different hysteresis loops with various directions and widths by changing bias current.[25] Compared with the optical bistability in the FP-LA, the optical bistability at dominated mode has high on/off contrast ratio resulting from side-mode injection locking in SMFP-LD, whose loop width is easily controlled by changing the wavelength and power level of the injection beam. Based on these significant characteristics, SMFP-LD-based bistability technology should be further explored and demonstrated in optical application. Therefore, it is significant to observe and investigate he optical bistability hysteresis for better seeking its applications in SMFP-LD. Based on the above comments, we present and demonstrate in detail the effects of wavelength detuning and injection power on the optical bistability behavior in this work, where we observe hysteresis loops with different widths and directions by changing the injection power and wavelength detuning in the SMFP-LD.

2. Experimental setup

The experimental setup for observing optical bistability in the SMFP-LD is depicted schematically in Fig. 1, in which the polarization state of a continuous wave generated by tunable laser (TL) can be controlled by the polarization controller (PC), and part of the continuous wave is injected into the SMFP-LD finally. The input power level of a TE mode

*Project supported by the National Natural Science Foundation of China (Grant No. 61205111), the Open Foundation of State Key Laboratory of Millimeter Waves, China (Grant No. K201219), and the Natural Science Foundation of Chongqing Normal University, China (Grant No. 2011XLZ06).

†Corresponding author. E-mail: jwwu@cqnu.edu.cn

© 2013 Chinese Physical Society and IOP Publishing Ltd

laser can be arbitrarily adjusted by the variable optical attenuator (VOA), which is equally divided into two beams by a coupler with 50/50 split ratio. One of the beams after coupler is injected into SMFP-LD through the circulator, and the other enters into the power meter to indirectly measure the injected power into the SMFP-LD. The output spectrum can be observed by using optical spectrum analyzer (OSA). Figure 2 shows the output of the injection locked SMFP-LD with the external beam injected into one of the side modes of the SMFP-LD under the condition of bias current of 15 mA and operation temperature of 14 °C. We can see that the wavelength of injected beam is slightly higher than that of one of the free running SMFP-LD side modes. The difference in the wavelength is known as wavelength detuning. The dotted line represents the output of SMFP-LD without any external probe beam. The solid line refers to the output from the SMFP-LD with the external injected beam. In the experiment, we focus on the power change at dominated and injected mode shown in Fig. 2 against the external injection power level, in which the peak wavelength of dominated mode is ∼1545.58 nm, and the peak wavelength of selected side mode in free running spectrum is ∼ 1550.26 nm.

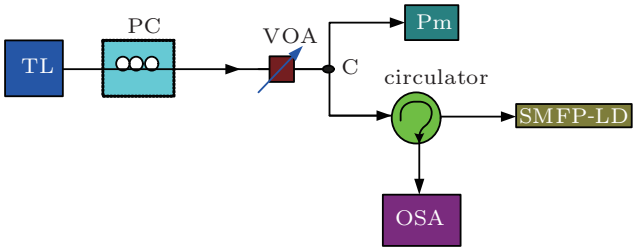


Fig. 1. (color online) Experimental setup for optical bistability based on the SMFP-LD: TL: tunable laser. PC: polarization controller. VOA: variable optical attenuator. C: coupler (50:50). Pm: power meter. SMFP-LD: single mode Fabry–Pérot laser diode. OSA: optical spectrum analyzer.

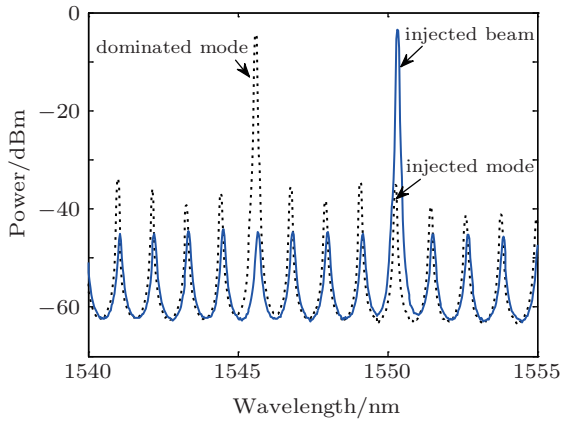


Fig. 2. (color online) Measured spectra for self-mode locking SMFP-LD (dotted line) and injection locking (solid line).

3. Experimental results and discussion

To observe the hysteresis loop in the SMFP-LD, we gradually increase the power of the injected beam, and simultaneously observe the output power levels of the dominant mode and the injected mode until the dominant mode is suppressed enough with the high on/off contrast ratio. Then, by slowly reducing the power of injected beam, we observe the dominant mode power until it recovers its free running initial state. Finally, the hysteresis loop is plotted based on the achieved experimental data with input injected beam power for different wavelength detunings. In the experiment, system parameters including bias current, operation temperature, and injection mode, are the same as those in Fig. 2.

In the SMFP-LD, optical bistability is strongly dependent on the injected power and wavelength detuning whose combined effect is the direct physical mechanism of leading to the output hysteresis loop. Figure 3 shows the corresponding hysteresis curves of dominant mode as a function of injection power with different wavelength detunings. In order to clearly discuss the physical mechanism of bistability behavior, we focus on the case of Fig. 3(c), where the wavelength detuning is 0.084 nm. When the injected power is initially set to be a value of −6 dBm (marker ①), the power of the dominant mode is about −5 dBm level. However, as the injected power is increased to −5 dBm outside the loop, the dominant mode is fully suppressed so that the output laser is locked at the injected wavelength (marker ②). On the contrary, after the injection power is again decreased to −6 dBm, the output determined mode still has a low output state (marker ③). To make the dominant mode return to its high output state, the injected power is slightly decreased to −6.2 dBm (marker ④), and then increased back to −6 dBm (marker ① again), thus completing the hysteresis loop. It is noticeable that the corresponding modulation depth as a value from high-output state to low-output state can reach a high level of ∼ 40 dB. In addition, when the wavelength detuning is increased to 0.112 nm, the hysteresis loop width is also extended, which is illustrated in Fig. 3(d) since wavelength detuning is directly proportional to input injection power for the suppression of dominant mode. This is because higher injection power (−4.2 dBm) is required to suppress the determined mode in the case of detuning of 0.112 nm with the result that the loop width is remarkably broadened compared with the case of Fig. 3(c). Another issue is that the clockwise hysteresis is exhibited in the above two cases. However, as the wavelength detunings decrease to 0.028 nm and 0.056 nm, completely different hystereses can be observed, which are shown in Figs. 3(a) and 3(b), where it is evident that the loop width is remarkably reduced due to the fact that lower input powers (−9.5 dBm and −8.5 dBm) are required for injection locking. In addition, there are some noticeable issues that are the counterclockwise hysteresis that is observed in the case of detuning of 0.028 nm, and a butterfly hysteresis loop that appears when the detuning is increased to 0.056 nm.

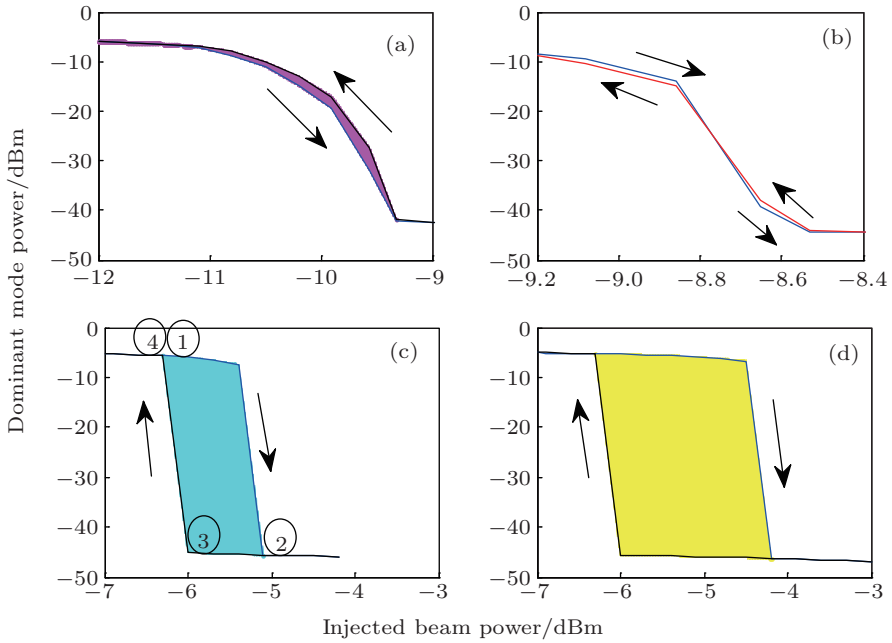


Fig. 3. (color online) Hysteresis curves of the dominant mode against the injected power for various wavelength detunings, (a) 0.028 nm, (b) 0.056 nm, (c) 0.084 nm, (d) 0.112 nm.

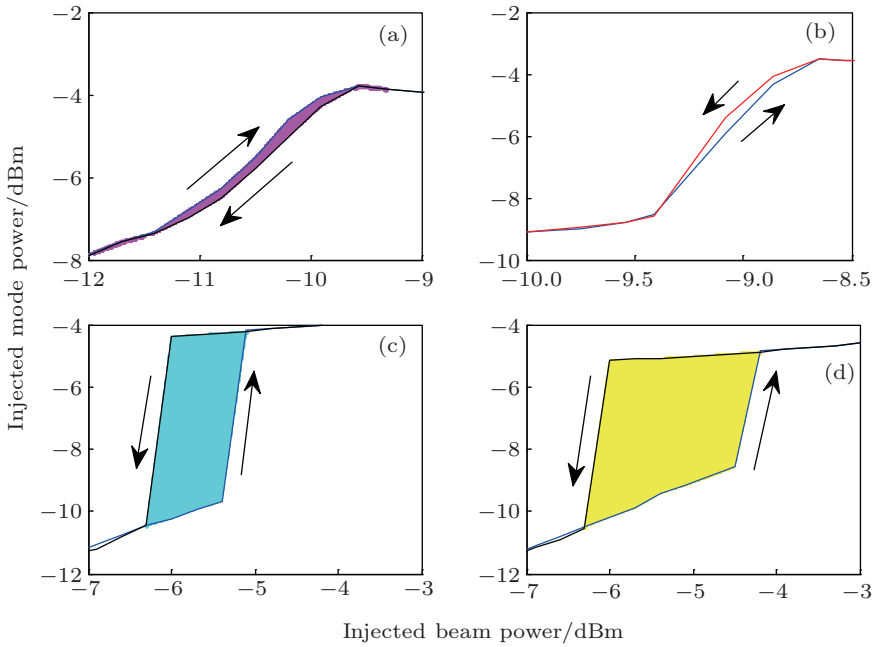


Fig. 4. (color online) Hysteresis curves of the injected mode power as a function of the injected beam power with various wavelength detunings, (a) 0.028 nm, (b) 0.056 nm, (c) 0.084 nm, (d) 0.112 nm.

In reality, the optical bistability shown in Fig. 3 exhibits a transition from counterclockwise to clockwise hysteresis in a way of a butterfly hysteresis when the detuning is increased from 0.028 nm to 0.112 nm. In contrast to the case of dominated mode, it is well understood that the output of the injected side mode also exhibits the optical bistability phenomenon, which is shown in Fig. 4. Compared with the hysteresis in Fig. 3, the hysteresis direction is reversed under the condition of the same detuning for injected side mode except for the case at wavelength detuning of 0.056 nm, and the obtained optical modulation depth is less than 10 dB. From the above discussion we can conclude that injection locking in SMFP-LD with small wavelength detuning such as 0.028 nm is good for the high speed switching and control circuit. On the other hand, higher wavelength detuning such as 0.112 nm can be used for optical memory and flip–flop, which provides the wider width of hysteresis loop. According to Figs. 3 and 4, we should point out that the loop width is compressed to minimum in

the case of wavelength detuning of 0.056-nm, where the obtained bistability loop for dominated mode is a transition between clockwise and counterclockwise hysteresis. Through the experiment, we find that the achieved hysteresis loop at 0.056-nm wavelength detuning is not very stable, owing to the enhanced mode competition with the result that the plotted bistability loop is also unstable, and is very sensitive to the operation condition such as external injection wavelength. As a consequence, one can only see a butterfly loop with very narrow width in the dominated mode as shown in Fig. 3(b). In this case, it is very difficult to observe an obvious butterfly loop for the corresponding injected mode in Fig. 4(b), in which the butterfly hysteresis is nearly absent. Even so, we believe that while wavelength detuning is tuned from 0.028 nm to 0.112 nm based on above system parameters, three types of hysteresis loops including clockwise, counterclockwise, and butterfly can be, respectively, observed by carefully tuning the injection wavelength.

The optical bistability induced by the injection power is observed and discussed. The effect of wavelength detuning on the hysteresis curve is illustrated in Fig. 5, where the counterclockwise and clockwise hysteresis loops are, respectively, exhibited against the wavelength detuning for the dominant mode and injected mode with three different injected powers of −7 dBm, −6 dBm, and −5 dBm. When the injected power of −7 dBm is coupled into the SMFP-LD, the loop widths shown in Figs. 5(a) and 5(d) are very narrow since the low injected power will lead to the small locking range. On the contrary, the loop widths are significantly extended in the cases of injection powers of −6 dBm and −5 dBm, which can be seen in Figs. 5(b), 5(c), 5(e), and 5(f). This is because the enhanced injection power will broaden the locking range of SMFP-LD. In addition, note that loop widths are almost equal for the cases of dominant and injected mode hysteresis loops due to the saturation effect. Besides the hysteresis loop width, we can also see a directly proportional relationship between wavelength detuning and input injected power required for the suppression of the dominant mode.

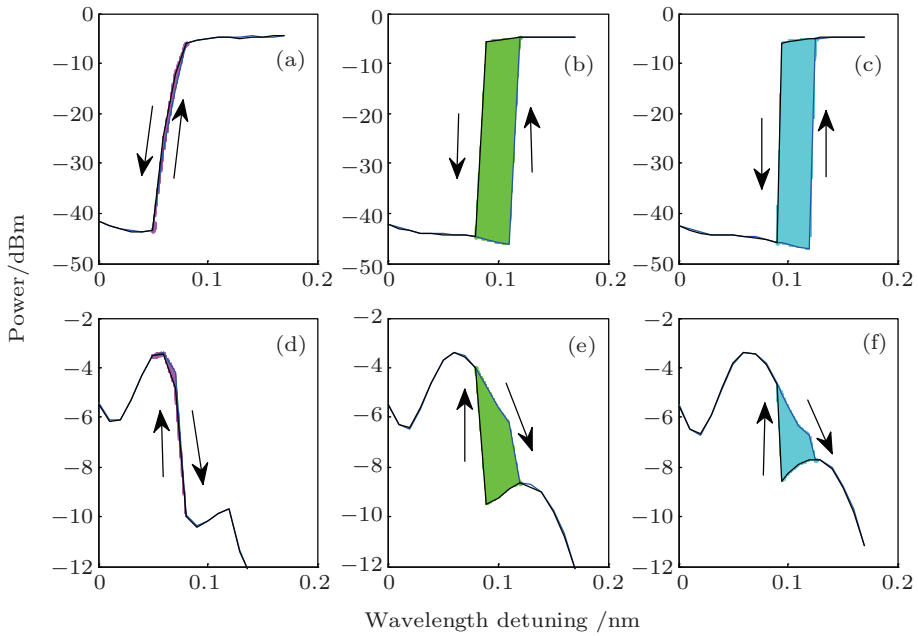


Fig. 5. (color online) Hysteresis curves of the dominant mode [panels (a)–(c)] and injected mode [panels (d)–(f)] versus the wavelength detuning with enhancing injection beam power.

4. Conclusions

We have thoroughly investigated the optical bistability induced by the power of injected beam and wavelength detuning based on the self-mode locking single mode Fabry–Pérot laser diode. The transitions of hysteresis direction from counterclockwise to clockwise and from clockwise to counterclockwise are observed for the dominant mode and injected mode powers, respectively, through the butterfly hysteresis. The enhanced loop width can be obtained by increasing the wavelength detuning. In addition, to obviously observe the bistability properties as a function of the wavelength detuning, the high injection power should be selected. However, the loop width will trend to a stable state, owing to the injected saturation effect inside the SMFP-LD. So, it can be concluded that the nonlinear optical bistability is the direct result of the combined effect of injected beam power and wavelength detuning.

Acknowledgment

The authors would like to thank Prof. Yong-Hyub Won and Mr. Tran Quoc Hoai for their useful discussions.

References

[1] Goelho A G, Queiroz A S B, da Silva M G, Lyra M L and Sombra A S B 2013 *Commun. Nonlinear Sci.* **18** 1258
[2] Zamora-Munt J and Masoller C 2010 *Opt. Express* **18** 16418
[3] Tsukada N and Nakayama T 1982 *Phys. Rev. A* **25** 964
[4] Huybrechts K, Tanemura T, Takeda K, Nakano Y, Baets R and Morthier G 2010 *IEEE J. Sel. Top. Quant.* **16** 1434
[5] Li P, Wang Y C and Zhang J Z 2010 *Opt. Express* **18** 20360
[6] Brandonisio N, Heinricht P, Osborne S, Amann A and O'Brien S 2012 *IEEE Photon. J.* **4** 95
[7] Li H, Sheng C X and Chen Q 2012 *Chin. Phys. Lett.* **29** 054201
[8] Li J B, Kim N C, Cheng M T, Zhou L, Hao Z H and Wang Q Q 2012 *Opt. Express* **20** 1856
[9] Zheng Q, Li S C, Zhang X P, You T J and Fu L B 2012 *Chin. Phys. B* **21** 093702
[10] Chen A X, Wang Z P, Chen D H and Xu Y Q 2009 *Chin. Phys. B* **18** 1072
[11] Liu J H, Wan Y, Han W J, Yang H W, Zhang H J, Wang J Y and Petrov V 2010 *Acta Phys. Sin.* **59** 293 (in Chinese)
[12] Agrawal G P and Dutta N K 1984 *J. Appl. Phys.* **56** 664
[13] Hui R, Paradisi A, Benedetto S and Montrosset I 1993 *Opt. Lett.* **18** 1733
[14] Hurtado A, Gonzalez-Marcos A and Martin-Pereda J A 2005 *IEEE J. Quantum Electron.* **41** 376
[15] Wen P Y, Sanchez M, Gross M and Esener S C 2006 *Appl. Opt.* **45** 6349
[16] Alexandropoulos D, Simos H, Adams M J and Syvridis D 2008 *IEEE J. Sel. Top. Quant.* **14** 918
[17] Almeida V R and Lipson M 2004 *Opt. Lett.* **29** 2387
[18] Jeong Y D, Won Y H, Choi S O and Yoon J H 2006 *Opt. Lett.* **31** 2586
[19] Yang Y B, Wang Y C, Zhang M J and Liang W 2007 *Chin. Phys. Lett.* **24** 1573
[20] Nakarmi B, Rakib-Uddin M and Won Y H 2011 *IEEE J. Lightwave Technol.* **29** 3015
[21] Nakarmi B, Rakib-Uddin M, Hoai T Q and Won Y H 2011 *IEEE Photon. Technol. Lett.* **23** 236
[22] Rakib-Uddin M andWon Y H 2010 *IEEE Photon. Technol. Lett.* **22** 290
[23] Nakarmi B, Rakib-Uddin M, Hoai T Q and Won Y H 2011 *IEEE Photon. Technol. Lett.* **23** 212
[24] Hoang N L, Cho J S, Won Y H and Jeong Y D 2007 *Opt. Express* **15** 5166
[25] Mitchell N F, O'Gorman J, Hegarty J and Connolly J C 1994 *Opt. Lett.* **19** 269