Experimental Study of a Semiconductor Laser Diode

Having a Mach-Zehnder Interferometer in the Cavity

Kohki Mukai and Takurou Imai

Yokohama National University,

79-5 Tokiwadai, Hodogaya-Ku, Yokohama 240-8501, Japan

FAX: +81-45-339-3853, email: mukai@ynu.ac.jp

ABSTRACT

We have studied experimentally the performance of a semiconductor laser diode that has an asymmetric Mach-Zehnder interferometer all-optical switch in the cavity. This novel device was designed to be free from clock pulse insertion, since mode-locked optical pulses are generated internally and change the balance of the interferometer periodically. We fabricated the device using the InGaAsP/InP buried heterostructure and investigated the primary optical properties of the device. We observed lasing characteristics that were peculiar to the twin-cavity structure, i.e., continuous-wave lasing power oscillation in relation to the injection current balance between the two arms, and cyclic changes in the single/multiple emission peaks as a function of bias voltage at the saturable absorber. Electrical spectrum analysis indicated 40-GHz modulation of lasing output from the twin-cavity laser.

Key words: semiconductor laser, twin cavity, Mach-Zehnder interferometer,
mode-locked laser

1 Introduction

In order to adapt the enormous increase in data traffic to data communication applications, high-capacity photonic networks have been subjected to intense scrutiny. All-optical signal handling devices represent a key technology to increase data capacity for future wavelength-division multiplexing (WDM) and optical time-division multiplexing (OTDM) systems [1, 2]. Compact semiconductor devices are attractive as cost-effective all-optical systems. Several types of semiconductor all-optical switching devices have been proposed and developed [3-6]. Among these, devices integrated with a Mach-Zehnder interferometer (MZI) have attracted significant attention because of their abilities to operate capability at speeds greater than 1 Tb/s [7]. For control of switching timing, these devices require the incorporation of optical clock pulses, which are usually generated by mode-locked lasers [8, 9].

We have proposed a unique all-optical switching device that integrates the functions of an interferometer and mode-locked laser in a single cavity [10]. The device is based on the colliding pulse passive mode-locked laser [11], and its cavity has twin arms that compose an asymmetric MZI [12]. An internal mode-locked optical pulse switches the data pulse train inserted into the cavity so that no external optical clock is required. The optical gate timing synchronizes automatically to the inserted pulse train when the carrier density in the saturable absorber (SA) is modulated by the inserted pulses. We have demonstrated theoretically the basic properties of the

switching device using the traveling wave equation model [13, 14].

Although there have been no reports of a laser with two such optical paths in the cavity, similar laser diodes with a longitudinally separated cavity have been investigated both theoretically and experimentally. One of these is a ‘twin-stripe’ laser, in which the upper electrode and the upper cladding layer are divided longitudinally by a groove [15]. The lateral mode pattern and bistability of the output power are controlled by the balance of currents injected into the separated electrodes. Another laser diode is the ‘twin-guide’ laser, in which the cavity is separated vertically so as to separate the functionalities [16, 17]. The spacer layer separates the lower emitting region and the upper index-tuning region for the selection of lasing wavelength. The upper region is also used as a mode selector. Since the two divided regions of these previously described lasers share the optical field, the cavity is actually a single unit. The MZI-type laser that we have proposed is unique in that it has a completely separated twin cavity, so its characteristics are expected to be unique.

In the present paper, we report an experimental study of twin-cavity semiconductor lasers that have an MZI in the cavity. The 1.5- μm -emitting InGaAsP/InP laser diode was fabricated as a buried heterostructure using the semiconductor monolithic integration technique. We investigated the primary lasing properties of the MZI-type device.

2 Operational Design of the Twin-Cavity Device

The structure of the device is shown schematically in Figure 1(a). The device components comprise two semiconductor optical amplifiers (SOAs), which work as nonlinear waveguides and gain mediums simultaneously, two multimode interferometers (MMIs), which function as 3-dB couplers, two mirrors, and a SA. Since an anti-reflective coating should be applied to the chip edge for input/output ports A and B, etched mirrors are good choices for the mirrors at the cavity edges [17]. Fortunately, the device does not require optical output behind the mirrors. These are connected by a passive waveguide to compose a cavity of the asymmetric MZI.

The operational principle of the device for switching is as follows. Two SOAs are initially balanced to attain optical feedback between two mirrors. In this situation, a pulse inserted from port A is transmitted to port B due to the symmetry. The device works as an optical gate when mode-locked lasing occurs between two mirrors. The operational process has two states that correspond to the relationship between the internal pulse and inserted signal pulse, i.e., copropagation or counterpropagation. For simplicity, we disregard the influence of the signal pulse on the balance of the interferometer. The internal pulse changes periodically its direction of propagation during the roundtrip, while the inserted signal pulses propagate in one direction. The key point is that the MZI is asymmetric. During copropagation timing, the signal pulse is sent to cross port B (i.e., the gate is open) because the phase of the signal pulses in the two arms experiences the same shift in the SOAs. During counterpropagation timing, the signal pulse in one arm does not suffer phase shift

before the internal pulse reaches the SOA. The signal pulse then proceeds to the saturable absorber (i.e., the gate is closed). Thus, the optical gate opens and shuts according to the repetition frequency of mode-locked lasing. The gate window width is determined by the positioning gap of the SOAs. When the frequency of mode-locked lasing is half that of the signal, every other input pulse passes through to the exit cross port and the remaining input pulse is absorbed by the SA. As a result, the device works as a 1/2 demultiplexer. The gate timing can synchronize to the signal input without an external clock recovery system when the carrier density in the SA is modulated by the half-input signal at 1/2 demultiplexing.

The mode-locked lasing occurs with the Mach-Zehnder-type cavity as follows. There are four variants of the light paths during a roundtrip in the cavity, i.e., a combination of two forward and two reverse routes. The balance between the two arms is very important for the operation of the device. If the two arms are not optically equal, the four routes are not equal. All routes are effective to some extent, even in the latter case, since each light must be divided at the MMI couplers. Then, when the lights from two arms are recoupled at the other coupler, the uncoupled light is released to the outside via the counter port to the mirror. Since the released light is regarded as a waveguide optical loss, lasing occurs when the optical gain is sufficient. In addition, timing jitter is generated with the slightly unequal arms. In this case, the jitter does not diminish and has an affect on device operation. However, the optical length of the arms can be adjusted to diminish the jitter by controlling the SOA currents. Even if

there is residual jitter, the delayed (or advanced) uncoupled light loses half of its power for every passage through the MMI coupler. Thus, the balance of the arms predominates over the optical loss, jitter, and resulting mode-locked lasing operation.

For practical applications, certain features of the device are noteworthy. To eliminate the influence of inserted signals on mode-locked lasing, either the power of the signals should be much smaller than the power of the internal pulses or the signal wavelength should be longer than the band edge of the SOA (even in this case, the device switches signals as predicted by the Kramers-Kronig relation [19]). When the arms are not well balanced, the inserted pulse is partially reflected from the mirror and propagates back into the interferometer. Even if the signal pulses do not affect the lasing operation, this will cause noise in the output signal. Therefore, arm balance is significant also from this viewpoint. There are many possible reflection points inside the integrated device, e.g., the joints of the passive/active sections. The optically optimized structural design and the best fabrication technique must be used to minimize these potential problems.

3 Experiments

The twin-cavity laser diode was fabricated using the semiconductor monolithic integration technique. The structure was grown by metalorganic vapor phase epitaxy on a (100)InP substrate. The MMIs, SOAs, SA, and etched mirrors were monolithically integrated with the 1- μm -wide passive waveguide. An optical

microscope image of the device is shown in Figure 1(b). The cavity length was designed to be 2.4 mm, which corresponds to the 20-GHz mode-locked operation. The SOA and SA had the same active layer, and the lengths were 400 μm and 50 μm , respectively. The component details and the monolithic integration techniques are the same as those reported previously [20, 21]. The InP/InGaAsP buried heterostructure allowed us to reduce the SOA current and the radius of curvature of the bending waveguide (we adopted $R = 600 \mu\text{m}$ in this device). The emission wavelength of the SOA active layer was 1.54 μm , and that of the passive waveguide core was 1.3 μm . The (14.5- $\mu\text{m} \times 320\text{-}\mu\text{m}$) MMI was designed as a 3-dB coupler for a wavelength of 1.54- μm . A butt joint was adopted at the connection of the components. Reflections at the MMI interfaces and the active/passive butt-joint were minimized so as to be negligible, which was checked with the other test structure. The widths of the input and output waveguides were tapered near the cleaved edges, where the antireflection coating was applied. The 8- μm -deep hole around the etched mirror was fabricated by inductively coupled plasma (ICP) reactive ion etching. The waveguide edge at the etched mirror was coated with Au metal by sputtering followed by plating in the electrode formation process. The reflectance of the etched mirror was expected to be >90% with the Au coating. The chip was mounted on a 2-mm-long diamond heat sink.

The optical properties of the device were evaluated with the tapered optical fiber coupled to the chip output port B. The chip temperature was controlled by a Peltier device. Optical power was measured using a fiber-in optical power meter.

Emission spectra were observed using an optical spectrum analyzer. The modulation frequency of the lasing power was measured using a radio frequency (RF) electrical spectrum analyzer. For the measurements, we amplified the optical output using a laboratory-made semiconductor optical amplifier, since the lasing wavelength was not covered by the Er-doped fiber amplifier (EDFA). The amplified optical signal was detected using an InGaAs photodiode with 50-GHz detection bandwidth.

4 Results and Discussion

Light outputs versus current characteristics are shown in Figure 2(a). For these measurements, two SOAs were connected electrically in parallel, and the circuit for the SA was opened. The current was varied between 0 mA and 160 mA; the emission spectra at 60 mA are shown in Fig. 2(b). We observed that lasing did not occur until the current was increased to 130 mA. Once lasing occurred, the lasing operation was maintained until the injected current was decreased to 45 mA. The low threshold current of 45 mA suggests that the optical cavity loss was not very large, even with several potential origins, such as the etched mirror, butt joint, and waveguide bending. The bistable characteristic was possibly caused by the nonlinear dynamics in the SA [6]. The delicate balance of the MZI-type cavity may also affect the lasing probability. Figure 2(b) indicates that the lasing wavelength was considerably shorter than the material band edge. This was caused by the suppression of optical gain near the band edge due to optical absorption at the SA.

We also evaluated the balance of twin arms since it dominates the interference of optical pulses and the resulting occurrence of mode-locked lasing. Figure 3(a) represents the results of the evaluation. For these measurements, the current of one SOA (I_{SOA1}) was varied while the current of the other SOA (I_{SOA2}) was fixed. A positive current of 20 mA was applied to the SA to prevent optical absorption. In Figure 3(a), two cases are compared, i.e., $I_{SOA2} = 100$ mA and $I_{SOA2} = 200$ mA. Considering that the lasing threshold current was 45 mA, this current is less than half that of I_{SOA2} , it is clear that continuous-wave lasing occurred for most of the measurements.

Figure 3(a) indicates that the lasing output power oscillated as I_{SOA1} was increased. This characteristic has never been observed for other semiconductor lasers in which the carrier density is clamped after lasing. The unique characteristic of this device is that the optical feedback changes depend on arm balance. It should be noted that there is no optical output in principle when the interferometer is perfectly balanced. However, as is evident in Figure 3(a), the light output was not minimal when the injection current was common to both SOAs. It is also clear that the light output did not reach to zero even at the minimal points. These results demonstrate that the two arms were not fabricated equally. For the non-zero optical output at the minimal point, there are three possible problems that are attributable to inaccuracies in the fabrication of the device and should be unavoidable: 1) unequal optical amplification at the SOAs; 2) unequal optical loss between the arms; and 3) non-bisectional

divergence ratio at the MMI couplers. The MMI was designed for a wavelength of 1.54 μm , whereas the actual lasing wavelength was less than 1.51 μm . This wavelength mismatch of 0.03 μm is expected to cause a divergence shift of only 3%, and therefore, this is not regarded as the main origin of the unbalanced arms.

The basic behavior depicted in Figure 3(a) is explainable as the average output after interference of a continuous-wave light beam. It is generally necessary to consider the nonlinear effects of the device in order to understand precisely the dynamic characteristics associated with the two arms [22, 23]. However, our rough simulation in Figure 3(b) explains the observed measurements. We estimated the output power oscillation that resulted from interference of continuous-wave light beams from the unbalanced MZI. We assume that the divergence ratio at the MMI coupler obeys the sine function of the optical phase, and that the phase in each arm is linear with respect to the SOA current. In addition, the total optical power increases as I_{SOA1} increases, whereas the optical leak from the MZI decreases as the mismatch of optical path length is reduced. We describe these increases and decreases using the simple sine function, with the frequency determined by I_{SOA2} . Thus, the output power oscillation was estimated as the multiplication of the square of two sine functions, as indicated in Figure 3(b). In this calculation, we assume that the injection current of 40 mA in SOA 1 corresponds to the phase shift of $\pi/2$, and that the mismatch of path length is minimized when I_{SOA1} is 10% greater than I_{SOA2} . The result suggests that the characteristics shown in Figure 3(a) are dominated by the interference in the

unbalanced arms.

Figure 4 represents the lasing spectra with various negative bias voltages applied to the SA. For these measurements, the SOA currents were set at 200 mA and 210 mA, which were chosen to minimize optical output when the circuit of the SA was opened. The emission spectra suggest that the number of peaks changed in relation to the bias voltage at the SA. The peak wavelength is plotted in Figure 5. As the bias voltage was decreased from -0.01 V to -2.21 V, the number of peaks cycled twice between single and multiple. This cyclic characteristic has never been observed for the ordinary, single-cavity, mode-locked laser diode.

One explanation for the unique cyclic characteristic of our device is that the cavity loss due to the interferometer changes periodically according to the optical absorption at the SA. The absorption changes the optical feedback into each arm, and the resulting carrier density in the SOA. When the two SOAs in the two arms are not equal, as in this case, the common change of optical feedback shifts the balance of the two arms. Our calculations assuming that the injection current of 25 mA in SOA 2 corresponds to a phase shift of $\pi/2$, with 40 mA in SOA 1, suggested that the optical leakage from MZI oscillates twice as the optical absorption at SA changes from 0% to 100 %.

The passively mode-locked operation of the device was investigated. We searched for the electric condition under which the RF spectrum of the lasing power shows a sharp peak. Figure 6(a) shows that the signal at 39.86 GHz corresponds to the

second order harmonic frequency of the cavity. The currents injected into the SOAs were 74 mA and 78 mA (i.e., the discrepancy was +5%), respectively, and the saturable absorber was biased at +1.23 V. The inset of Figure 6(a) shows the peak broadening, which is indicative of the large timing jitter of passively mode-locked semiconductor lasers. With a slight change of arm balance, the output power (i.e., optical loss for internal mode-locked lasing) increased and the timing jitter worsened, as shown in Figure 6(b), when the injection currents were 76 mA and 100 mA (i.e., the discrepancy was +32%), respectively. Under the other electrical condition (e.g., $I_{\text{SAO1}} = 53 \text{ mA}$, $I_{\text{SAO2}} = 61 \text{ mA}$, $V_{\text{SA}} = +0.76 \text{ V}$), the peak at 20 GHz became comparatively sharp and strong.

It should be noted that a distinct sharp peak was not observed in the RF spectra with negative SA bias voltage. We suppose that the unequal twin cavity, i.e., large cavity loss, restricted the modulation of lasing with negatively biased SA. In addition, it seems unlikely that high-frequency modulation was achieved with the positive SA bias voltage. The shortness of the carrier lifetime with positive bias voltage makes it unsuitable for mode-locked lasing. We suppose that some unexpected origins, such as point defects, caused the short carrier lifetime in the SA. This type of defect may have been created during the fabrication of the etched mirror that was coated with Au metal. Alternatively, it is possible that phase correlation between the longitudinal mode enabled passive mode-locking without SA under continuous-wave operation [24, 25].

To achieve good switching function with this device, it is necessary to have stable, low-noise, mode-locked lasing. For this purpose, the problems that originated by unavoidable errors in device fabrication must be compensated for after fabrication. This is possible with the insertion of a voltage-driven adjustable phase shifter into the asymmetric interferometer. The unequal lengths of the optical paths can be corrected by the phase shifter if the difference in length is small. On the other hand, optical amplification at SOAs can be equalized by controlling the injection current independently. As for the divergence ratio of the coupler, it can be adjusted to bisectional using the well-optimized MMI structure, in which the divergence ratio is not (in principle) very sensitive to size deviations and wavelength variations. Once the intrinsic disequilibrium of the two arms is compensated for, the optical absorption at the SA does not affect arm balance. These improvements enable the stable modulation of lasing oscillation with the twin-cavity laser.

5 Conclusion

We have studied experimentally the performance of a twin-cavity semiconductor laser diode. This device is designed as an all-optical switching device based on an asymmetric MZI, and it does not require optical clock pulse insertion because the mode-locked internal optical pulse controls the inserted signal pulse train. We fabricated the twin-cavity laser structure as an InGaAsP/InP buried heterostructure using the semiconductor monolithic integration technique. The unique

lasing characteristics associated with the twin cavity are presented experimentally, and include the oscillation of output power in relation to SOA current and periodic single/multiple peaks in the emission spectra as a function of SA bias voltage. These characteristics can be explained in terms of the interference of the optical beam in the MZI. The RF spectrum of the optical output power suggests 40-GHz modulation of the lasing oscillation.

Acknowledgements

The authors are grateful to Dr. Haruhiko Kuwatsuka and Mr. Tsuyoshi Yamamoto for their significant assistance in the fabrication of the device.

References

1. K. R. Ludwig, St. Diez, A. Ehrhardt, L. Kuller, W. Pieper and H. G. Weber, IEICE Trans. Electron. **E81-C**, 140 (1998).
2. K. Shimano, T. Takahashi, M. Koga and Y. Takigawa, NTT Tech Rev. 1, 12 (2003).
3. J. Leuthold, C.H. Joyner, B. Mikkelsen, G. Raybon, J.L. Pleumeekers, B.I. Miller, K. Dreyer and C.A. Burrus, Electron. Lett., **36**, 1129 (2000).
4. M.L. Nielsen, J. Mork, R. Suzuki, J. Sakaguchi, and Y. Ueno, Optics Express **13**, 5080 (2005).
5. N. Yamamoto, T. Matsuno, H. Takai and N. Ohtani, Jpn. J. Appl. Phys. **44**, 4749

- (2005).
6. K. Takeda, M. Takenaka, M. Raburn, Y. Kanema, J. S. Barton, X. Song and Y. Nakano, Jpn. J. Appl. Phys. **46**, 1028 (2007).
 7. S. Nakamura, Y. Ueno, K. Tajima, J. Sasaki, T. Sugimoto, T. Kato, T. Shimoda, M. Itoh, H. Hatakeyama, T. Tamanuki and T. Sasaki, IEEE Photon. Technol. Lett., **12**, 425 (2000).
 8. S. Arahira, Y. Matsui and Y. Ogawa, IEEE J. Quantum Electron., **32**, 1211 (1996).
 9. K. Williams, M. G. Thompson and I. White, New J. Phys. **6**, 179 (2004).
 10. K. Mukai and H. Kuwatsuka, Jpn. J. Appl. Phys. **43**, L680 (2004).
 11. Y. K. Chen, M. C. Wu, T. Tanbun-Ek, R.A. Logan, and M. A. Chin, Appl. Phys. Lett., **58**, 1253 (1991).
 12. P. V. Studenkov, M. R. Gokhale, J. Wei, W. Lin, I. Glesk, P. R. Prucnal and S. R. Forrest, IEEE Photon. Technol. Lett. **13**, 600 (2001).
 13. D.J. Jones, L.M. Zhang, J.E. Carrol and D.D. Marcenac, IEEE J. Quantum Electron, **31**, 1051 (1995).
 14. M. B. Flynn, L. O'Faolain and T. F. Krauss Appl. Phys. Lett. **86**, 221104 (2005).
 15. M. Watanabe, S. Mukai, H. Itoh, H. Yajima, M. Saito and K. Hasegawa, J. Appl. Phys. **68**, 2599 (1990).
 16. M. Kohtoku, S. Baba, S. Arai and Y. Suemune, IEEE Photon. Technol. Lett., **3**, 225 (1991).
 17. M. C. Aman and J. Buus, *Tunable Laser Diode* (Artech House, Boston 1998).

18. T. Yuasa, T. Yamada, K. Asakawa, S. Sugata, M. Ishii, and M. Uchida, Appl. Phys. Lett., **49**, 1007 (1986).
19. R. de L. Kronig, J. Opt. Soc. Am., **12**, 547 (1926).
20. K. Mukai, H. Kuwatsuka, K. Morito, H. Soda, F. Futami and S. Watanabe, Proc. Optical Amplifiers and Their Applications (OAA 2002), Vancouver, Canada, OWC-4.
21. K. Mukai, H. Kuwatsuka, K. Morito, F. Futami and S. Watanabe, OSA Trends in Optics and Photonics, **77**, 217 (2002).
22. L.A. Jiang, M.E. Grein, H.A. Haus and E.P. Ippen, IEEE J. Sel. Top. Quantum Electron. **7**, 159 (2001).
23. H. Erzgraber, B. Krauskopf and D. Lenstra, SIAM J. Appl. Dynamic. Sys. **5**, 30 (2006).
24. K. Sato, Electron. Lett. **37**, 763 (2001).
25. J. Renaudier, G.-H. Duan, J.-G. Provost, H. Debregeas-Sillard, and P. Gallion, IEEE Photonic. Technol. Lett. **17**, 741 (2005).

Figure captions

Figure 1 (a) Schematic of the proposed all-optical switching device, which generates mode-locked control pulses in an MZI-type twin cavity, and (b) plan-view optical microscope image of the fabricated device.

Figure 2 Lasing characteristics of the device. (a) Light output versus current characteristics, and (b) emission spectra at the injection current of 60 mA.

Figure 3 (a) Measured light output as a function of I_{SOA1} , and (b) simulation with a simple static model.

Figure 4 Emission spectra with various bias voltages at the SA.

Figure 5 Multiple peak wavelengths as a function of bias voltage at the SA.

Figure 6 RF spectrum indicating approximately 40 GHz modulation of lasing emission with (a) $I_{\text{SOA1}} = 74$ mA, $I_{\text{SOA2}} = 78$ mA, and $V_{\text{SA}} = +1.23$ V: and (b) $I_{\text{SOA1}} = 76$ mA, $I_{\text{SOA2}} = 100$ mA, and $V_{\text{SA}} = +1.23$ V.

Figure1

Figure 1 K. Mukai et al.
Experimental Study of Semiconductor Laser Diode ...

Figure2

Figure 2 K. Mukai et al.
Experimental Study of Semiconductor Laser Diode ...

Figure3

Figure 3 K. Mukai et al.
Experimental Study of Semiconductor Laser Diode ...

Figure4

Figure 4 K. Mukai et al.
Experimental Study of Semiconductor Laser Diode ...

Figure5

Figure 5 K. Mukai et al.
Experimental Study of Semiconductor Laser Diode ...

Figure6

Figure 6 K. Mukai et al.
Experimental Study of Semiconductor Laser Diode ...