Novel Self-Switching Optical Gate Device with Internal Mode-Locked Pulses

Kohki MUKAI* and Haruhiko KUWATSUKA

Fujitsu Laboratories Ltd., 10-1 Morinosato-Wakamiya, Atsugi 243-0197, Japan

We propose a new all-optical gate device integrating a Mach-Zehnder interferometer in the cavity of a mode-locked laser diode. The device utilizes semiconductor optical amplifiers not only as gain mediums for the mode-locked emission but also as phase shifters for optical switching with the interferometer. The gate opens and shuts with the internal mode-locked optical pulses, eliminating the need for an external optical clock pulse for the switching. Gate timing can be synchronized to input data signals when the saturable absorber with passive mode-locked setup absorbs signal pulses. This function-integrated optical device will aid in reducing the size of future high-bit-rate data processing systems.

KEYWORDS: all-optical, interferometer, gate device, mode-locked laser, semiconductor optical amplifier

---

*E-mail : mukai@ynu.ac.jp / Present address : Division of Materials Science and Engineering, Graduate School of Engineering, Yokohama National University, 79-5, Tokiwadai, Hodogaya-Ku, Yokohama, 240-8501 Japan.

All-optical devices have been the subject of considerable research interest due to their potential applications in future high-bit-rate data transmission networks (1, 2) and many researchers have achieved various functions with high-speed all-optical signal processing such as mux/demux, wavelength conversion, and 3R-regeneration (3 – 7). For mass production, such devices will be required to meet practical demands such as having compactness, minimal power consumption, low cost and simplicity for manufacturing. From this perspective, compact solid devices, such as integrated semiconductor gate devices with interferometers (5 – 7) and mode-locked laser diodes as optical clock sources, (8, 9) have been studied in addition to fiber optic devices. Combined with timing adjustment circuits, these devices will be connected using optical waveguides in future all-optical signal processing units.

In this letter, we propose a new all-optical gate device integrated with a Mach-Zehnder interferometer in the cavity of a mode-locked laser diode. Since the internal mode-locked optical pulses work as control pulses, no external optical clock is required and the gate opens and shuts with the repetition frequency of the mode-locked lasing. We describe the concept of the device and demonstrate the simulation of basic gating characteristics.

Figure 1 schematically shows the optical gate device that we propose. The structure is based on the colliding pulse passive mode-locked laser setup (10, 11) and the components are two optical mirrors, two 2 x 2 three decibel couplers, two gain mediums (phase shifters), waveguides and a saturable absorber. The saturable absorber is not essential for the operation of this device since we can modulate the gain mediums electrically to generate active mode-locked lasing. The gate entrance is port A and the exit is port B and during the gate operation, internal optical pulses make roundtrips between the two mirrors. The key point is that the cavity has two arms composing the asymmetric Mach-Zehnder interferometer. Owing to the asymmetric structure, the internal roundtrip pulses periodically switch the interferometer, and the optical gate opens and shuts at that repetition frequency.

We explain the details of the operation principle in the following. We balance two phase shifters (gain mediums) to compose a cavity for mode-locked lasing between two mirrors. Once the internal mode-locked pulse reflected by the mirror is equally divided at the 3-dB coupler, half passes through each arm, and then rejoins at the other 3-dB coupler before being reflected again by the other mirror. For simplicity, we neglect the influence of the input signal pulse on the phase shifter and consider that due to the symmetry, the signal pulse from port A is sent across to port B without internal mode-locked pulses. We also neglect the occurrence of the roundtrip of the signal pulse in the device, assuming that port B has no reflection and that the saturable absorber completely absorbs the signal pulse. Figure 2 illustrates what happens when the optical signal is input at the timing of co-propagation and counter propagation versus the internal pulse direction. The exit port is periodically switched according to these two situations, due to the asymmetric Mach-Zehnder interferometer. With the co-propagation timing (Fig. 2(a)), the signal pulse is sent to port B (i.e., the gate is open) because the phases of the two pulses in both arms are the same at the second coupler. With the counter propagation timing (Fig. 2(b)), the signal pulse in one arm is not affected by the internal mode-locked pulses when it passes the phase shifter before the mode-locked pulse reaches the phase shifter. The gate is closed for the time window corresponding to the positioning gap of the phase shifter ($\Delta_{□□}$). The situation is like that of a Mach-Zehnder terahertz optical asymmetric demultiplexer (MZ-TOAD). (12)

We can design the gate timing and demux rate by arranging the position of the phase shifter in the cavity. A 100 μm positioning shift corresponds to about a 1 ps change of the gating point. When the gating frequency is half that of the signal, every other input pulse passes through to the exit port, and the rest are absorbed by the saturable absorber, this being a 1:2 demux operation. In this case, the carrier density in the saturable absorber is modulated at half the frequency of the input signal. Then, the gate timing will be adjusted to the timing of the signal input without any clock recovery system.

Next, we discuss how the mode-locked lasing occurs in the Mach-Zehnder cavity, focusing on the behavior of the optical pulse's roundtrips in the two arms. Let us assume that the pulse starts at mirror 1. You can see that there are four possible routes for the roundtrip: i) arm 1 (forward) to arm 2 (reverse), ii) arm 2 (forward) to arm 1 (reverse), iii) arm 1 (forward) to arm 1 (reverse), and iv) arm 2 (forward) to arm 2 (reverse). If optical pulses traveling along any of these routes suffer the exact same losses, gain and phase rotation, every route must have the same effectiveness, and a desirable switching operation can be obtained. The question is what will happen in the case when the four routes are not exactly equal; the gate will not work if the pulse only passes one phase shifter in one direction. However, such a situation never occurs and all routes have the same effectiveness even when the four routes are not equal. This is because the mode-locked pulses must always pass through the 3-dB couplers. The pulse reflected by mirror 1 is divided equally at the coupler. If the pulses are not affected exactly identically in the arms, almost all of the light is coupled at the other 3-dB coupler and travels to mirror 2, while the remainder of the uncoupled light is released outside via the exit port, and is regarded as waveguide loss. Mode-locked lasing will occur if there is sufficient gain.

We simulated the device characteristics by solving the traveling wave equations under the large signal dynamic model proposed by Zhang *et al*.. (13 – 15) The model incorporates gain saturation, spontaneous emission, the gain-frequency relation, and the line-width enhancement factor. We assumed a monolithic semiconductor device structure based on a InGaAsP/InP system, and used a semiconductor optical amplifier (SOA) as the gain medium and a multimode interferometer (MMI) as the 3-dB coupler. Figure 3 represents the device dynamics under the conditions of $\Delta_{\mathrm{gm}} = 600\ \mu\mathrm{m}$ with $L_{\mathrm{total}} = 1200\ \mu\mathrm{m}$. We set the SOA position so as to be symmetrical to the center point of the cavity. In order to obtain a good switching window, the SOA currents are set so they are out of balance. The temporal evolution of optical power demonstrates that the intentional mode-locked lasing occurs with the Mach-Zehnder cavity. The oscillation frequency that corresponds to the 1200 μm cavity length is approximetely 40

GHz. In the figure, we can also see that the phase oscillates with the frequency of mode-locked lasing. Since the SOA position is symmetric to the center point and the positioning gap is half the total cavity length, the valleys of the phase oscillations of arm 1 match the peaks of those of arm 2 (see inset). The phase gap between the two arms determines the transmittance of the gate device, and since the phase gap oscillates between almost 0 to π, the gate opens and shuts at the frequency of the mode-locked lasing.

The width of the switching window is a function of the positioning gap between two SOAs (Δ_{gm}); as the gap increases, the window width decreases. Figure 4 indicates the results of simulation with regard to the time evolution of the gate transmittance assuming $\Delta_{gm} = 300$ and 600 μm with $L_{total} = 1200$ μm. In both cases, periodic gating occurs at a common frequency. We can see that the window width is larger with $\Delta_{gm} = 300$ μm than with $\Delta_{gm} = 600$ μm; the device functions as a 1:1 periodic optical gate at $\Delta_{gap} = 600$ μm. The gating window widths in the figure are 18.5 and 13.5 ps, and the extinction ratios are 14 and 20 dB for $\Delta_{gm} = 300$ and 600 μm, respectively. Since we can design the window width and timing of the switching, this gate device will be applicable to various signal processing designs.

The device has several optional design factors. We can use higher ordered mode-locked lasing when the frequency of fundamental mode locking differs from the desirable one. This is valid since the minimum cavity length is limited by the size of the device components (e.g., SOA, MMI, and bending waveguide) and the SOAs' positioning gap. For this purpose, for example, a saturable absorber is added in front of mirror 1. In order to control the operation frequency precisely, we can also use a metal-coated etched mirror. (16) Since the etching position error is less than one tenth of that of cleaving, an accurate cavity length can be achieved with the etched mirror. The metal coating is a very effective way to obtain a high reflectivity and since the device does not need any output behind the mirrors for operation, using a metal-coated mirror reduces the cavity loss.

In summary, we have proposed a new all-optical gate device integrating a Mach-Zehnder interferometer in the cavity of a mode-locked laser diode. An internal mode-locked pulse periodically switches the asymmetric Mach-Zehnder interferometer, and the gate opens and shuts with the repetition frequency of the mode-locked lasing. The positioning gap between the two gain mediums determines the width of the gating window, and the relative position of the gain mediums in the cavity determines the gate timing versus the signal input. The gate timing can be synchronized to the signal input when the saturable absorber in the passive mode-locked setup absorbs some signal pulses. The device performance simply as a mode-locked laser diode or an optical switch does not surpass that of previous simple devices, but its compact integration makes it very attractive for future practical applications to all-optical data signal processing.

References

1) C. Janz: *Proc. Optical Fiber Communication Conf.,* (Baltimore, USA, 2000), pp. 90.

2) B. Sartorius: *Proc. Eur. Conf. Optical Communication,* (Munich, Germany, 2000), pp. 293.

3) B. Mikkelsen, M. Vaa, H. N. Poulsen, S. L. Danielsen, C. Joergensen, A. Kloch, P. B. Hansen, K. E. Stubkjaer, K. Wunstel, K. Daub, E. Lach, G. Laube, W. Idler, M. Schilling and S. Bouchoule: Electron. Lett. **33** (1997) 133.

4) J. Leuthold, C. H. Joyner, B. Mikkelsen, G. Raybon, J. L. Pleumeekers, B. I. Miller, K. Dreyer and C. A. Burrus: Electron. Lett. **36** (2000) 1129.

5) 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. Tech. Lett. **12** (2000) 425.

6) B. Mikkelsen, K. S. Jepsen, M. Vaa, H. N. Poulsen, K. E. Stubkjaer, R. Hess, M. Duelk, W. Vogt, E. Gamper, E. Gini, P. A. Besse, H. Melchior, S. Bouchoule and F. Devaux: Electron. Lett. **33** (1997) 2137.

7) K. Mukai, H. Kuwatsuka, K. Morito, H. Soda, F. Futami and S. Watanabe: *Proc. Optical Amplifiers and Their Applications,* (Vancouver, Canada, 2002), OWC-4.

8) S. Arahira, Y. Matsui and Y. Ogawa: IEEE J. of Quantum Electron. **32** (1996) 1211.

9) T. Shimizu, I. Ogura and H. Yokoyama: Electron. Lett. **33** (1997) 1868.

10) Y. K. Chen, M. C. Wu, T. Tanbun-Ek, R. A. Logan, and M. A. Chin: Appl. Phys. Lett. **58** (1991) 1253.

11) S. Arahira, S. Oshiba, Y. Matsui, T. Kunii and Y. Ogawa: Appl. Phys. Lett. **64** (1994) 1917.

12) P. V. Studenkov, M. R. Gokhale, J. Wei, W. Lin, I. Glesk, P. R. Prucnal and S. R. Forrest: IEEE Photon. Tech. Lett. **13** (2001) 600.

13) D. J. Jones, L. M. Zhang, J. E. Carroll and D. D. Marcenac: IEEE J. Quantum Electron. **31** (1995) 1051.

14) L. M. Zhang and J. E. Carroll: IEEE J. Quantum Electron. **31** (1995) 240.

15) L. M. Zhang, S. F. Yu, M.C. Nowell, D. D. Marcenac, J. E. Carroll and R. G. S. Plumb: IEEE J. Quantum Electron. **30** (1994) 1389.

16) T. Yuasa, T. Yamada, K. Asakawa, S. Sugata, M. Ishii and M. Uchida: Appl. Phys. Lett. **49** (1986) 1007.

Figure captions

Fig. 1: Schematics of the optical gate device proposed in this paper. The structure is based on the colliding pulse passive mode-locked laser setup, and the cavity has two arms which compose an asymmetric Mach-Zehnder interferometer. Internal mode-locked pulses make a roundtrip between two mirrors. Signal pulses are input at port A and exit via port B.

Fig. 2: Phase shift of the optical signal is input at the timing of (a) co-propagation and (b) counter propagation versus the internal pulse direction. With the co-propagation timing, influence of the internal mode-locked pulses on the phase of input signals is equal at the end of the arms. In this case, the signal exits via the cross port. With the counter propagation timing, the signal pulse in one arm is not affected by the internal mode-locked pulses when it passes the phase shifter before the mode-locked pulse reaches the phase shifter. Then, the pulse exits via the bar port.

Fig. 3: Time evolution of optical power of mode-locked pulses at mirror 1, and time evolution of the phase of two signal lights, one of which has passed arm 1 while the other has passed arm 2, at exit port B. Phase properties are expanded in the inset.

Fig. 4: Time evolution of gate transmittance assuming positioning gaps of 300 and 600 μm with a total cavity length of 1200 μm.

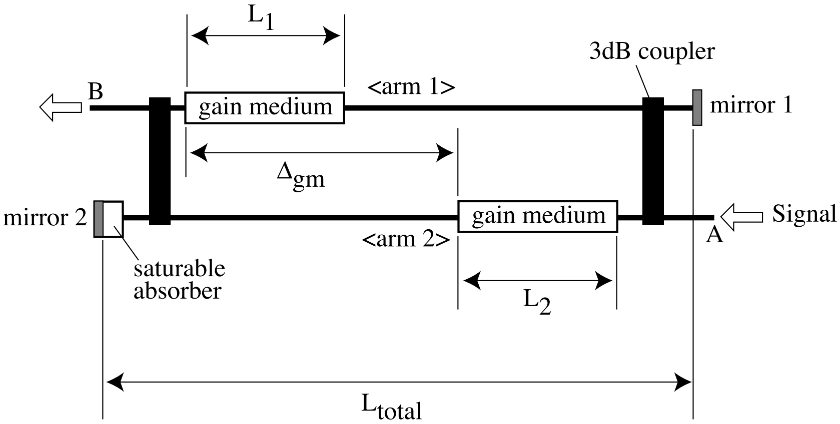
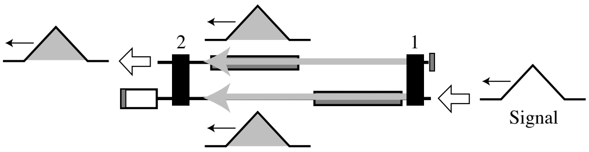

L1
3dB coupler
B
<arm 1>
gain medium
mirror 1
Δgm
mirror 2
gain medium
Signal
A
<arm 2>
saturable absorber
L2
Ltotal

Fig. 1

(a) co-propagation



(b) counter propagation

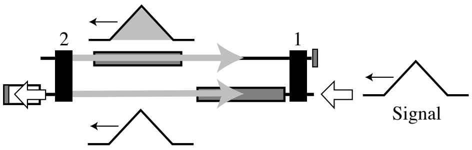


Fig. 2

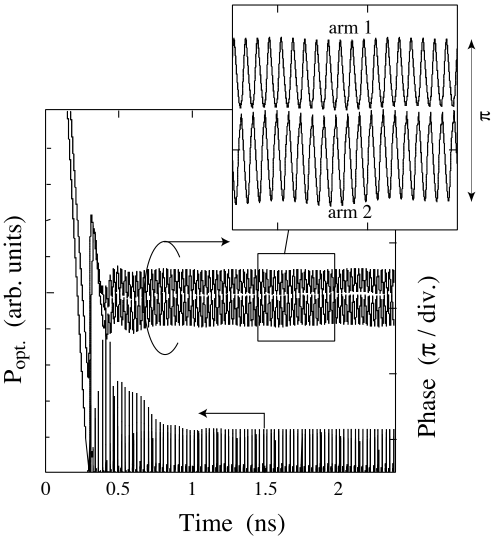


Fig. 3

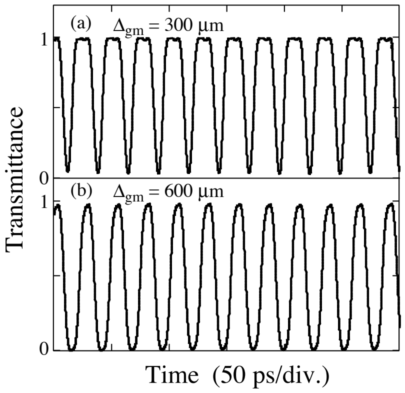

(a) Δ_{gm} = 300 μm
(b) Δ_{gm} = 600 μm
Transmittance
1
0
1
0
Time (50 ps/div.)

Fig. 4