九 州 大 学 大 学 院 総 合 理 工 学 報 告
第31巻　第1号　1-6頁　平成21年4月

Engineering Sciences Reports, Kyushu University
Vol. 31, No. 1, pp. 1-6, APR. 2009

Optical Bit-Memory Element Based on Bi-Stability between Different Lateral Modes Using Novel Active Multi-Mode-Interferometer (MMI) for Random Access Memory (RAM) Application

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(Received April 30, 2009)

A novel principle of active multi-mode-interferometer (MMI) bi-stable laser diode (BLD), utilizing different lateral modes, has been proposed and demonstrated for optical random access memory (RAM) application. The two different propagation modes realize two different identical paths in a single active MMI cavity simultaneously, with sharing exactly same port at one facet side. This novel concept contributes to realize relatively large cross-gain saturation region between the two identical paths, which result in stable bi-stability even in a relatively compact device size. Implemented devices showed relatively low operation current of 100mA and sufficient hysteresis window of 8mA with the cavity length of only 550μm. High optical ON/OFF ratio of more than 15dB was also confirmed successfully.

Key words: *active MMI, bi-stable laser diode, cross-gain saturation*

1. Introduction

Current internet routers consume huge amount of electrical power mainly due to OEO (optical / electrical / optical) signal exchanges. For example in Japan, the power consumption in internet routers was 0.22% at 2004, however, the data traffic is still increasing every year[1)], and thus, it is estimated that the power consumption will reach to 9% of the total power consumption in Japan at 2015[2)] (see Fig. 1). This leads to the necessity to develop all-optical routers that could result in energy conservation. Optical random access memory (RAM) is a key device for realizing such that all-optical routers especially for the buffering function. To date, several candidates of optical bit memory element for RAM application have been proposed[3-8)]. Among them, active multi-mode interferometer (MMI)[9-11)] bi-stable laser diodes (BLDs)[6, 8)] are attractive due to their relatively superior tolerance in fabrication.

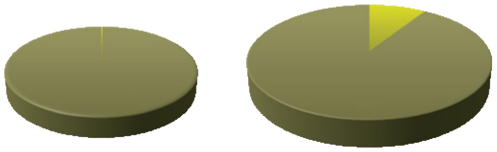

Fig. 1 Power consumption forecast at router in Japan[2)].

One critical issue for such that BLDs is, however, their long device length[6, 7)] due to their insufficient cross-gain saturation effect in a cavity which must be compensated by designing longer cavity length. To overcome this issue, we propose and demonstrate a novel principle of active-MMI BLD in this paper. The novel active-MMI BLD can act as an optical bit-memory element utilizing relatively long co-relation region between 0th-order and 1st-order mode paths, which lead to sufficient cross-gain saturation effect even in a relatively short cavity. Simulated results, by using beam-propagation-method (BPM)[12)], proved that the two different identical propagation paths of 0th-order and 1st-order modes existed

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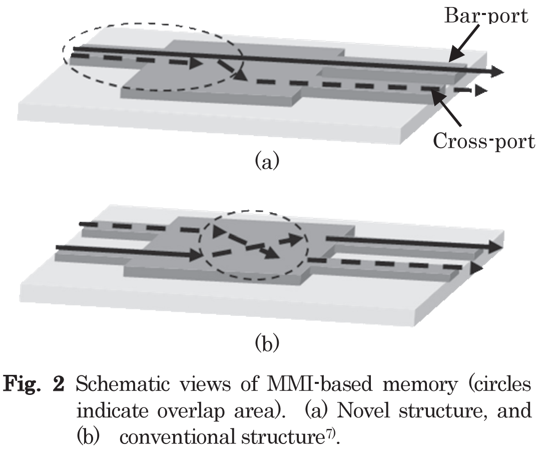
in a properly designed active MMI cavity. The actually implemented devices showed relatively low operation current of 100mA and sufficient hysteresis window of 8mA with a cavity length of only 550μm. High optical ON/OFF ratio of more than 15dB was also confirmed successfully.

In this paper, the concept of the novel active-MMI BLD is discussed in section 2. Then in section 3, we prove this novel concept by using BPM simulation. In section 4, we show the experimental results of the actually implemented novel active-MMI BLDs for the first time.

2. Concept

For active-MMI BLDs in general, cross-gain saturation region between two identical propagation paths lead to bi-stability characteristics, besides the absorption effect provided by saturable absorber[6, 7, 13]. In the configuration of previously reported symmetric active-MMI BLD[6, 7] shown in Fig. 2 (b), there are two access ports on each side, and two propagation paths. The area shown by dotted line is cross-gain saturation region between the two propagation paths. In this configuration, there are two factors contribute together to obtain bi-stability, namely, cross-gain saturation effect in addition to saturable absorption effect. Hence, in order to realize sufficient hysteresis window, we either design for sufficiently large cross-gain saturation region between the two identical propagation paths or increase the length of the saturable absorbers. To attain stable bi-stability and meanwhile preserve a compact device size, it is necessary to realize sufficiently large cross-gain saturation region between two propagation paths without increasing the length of the device. However, in the previously reported symmetric active-MMI BLD, indicated in Fig. 2 (b), the cross-gain region lies just only in the center of the MMI region, therefore, it is necessary to design relatively long MMI region that results in relatively large device size, to obtain stable bi-stability. To overcome this issue, we propose increasing the cross-gain saturation region by using different lateral propagation modes including 0th-order and 1st-order modes[14]. This leads to share one common port (shown Fig. 2 (a)) with two identical propagation paths so that the cross-gain saturation region is enhanced significantly without designing long active-MMI section. As is shown in Fig. 2 (a), the 0th-order mode propagates along the cross path and emerges from the cross-port while the 1st-order mode propagates along the straight path and emerges from the bar-port, and thus the two identical propagation paths can be achieved simultaneously in a single cavity. In such a configuration, the device can be set to the ON state using input-signal with regular 0th-order mode as a 1-bit memory operation.



(a)

(b)

Fig. 2 Schematic views of MMI-based memory (circles indicate overlap area). (a) Novel structure, and (b) conventional structure[7].

3. Design and Simulation

At first, we verify our scheme of utilizing 0th-order and 1st-order modes light propagation by using BPM simulation[12]. In this simulation, we used regular ridge structure for the waveguide[15, 16]. We designed the active layer with regular InGaAsP/InGaAsP multiple quantum-well structure whose band gap wavelength was set to be 1.55μm. To support the 0th-order and 1st-order modes while cutting off the 2nd-order mode on the access waveguides, the equivalent refractive indices of guiding and non-guiding regions were designed to be 3.2107 and 3.1725, respectively. And using these refractive indices, the access waveguide widths were designed to be 4μm by using Eq. (1)[15],

$$W_N \leqslant \frac{N\lambda}{2n_r}\sqrt{\frac{n_r}{2(n_r - n_c)}} \tag{1}$$

where, W_N is the access waveguide width, N is the mode number, n_r and n_c are the equivalent refractive indices of guiding and non-guiding, λ is the wavelength.

We set the MMI width (W_{MMI}) to be 10μm, and the optimum MMI length (L_{MMI}) which can realize cross-propagation for 0th-order while bar-propagation for 1st-order modes[14, 17] was designed by using Eq. (2) to (4),

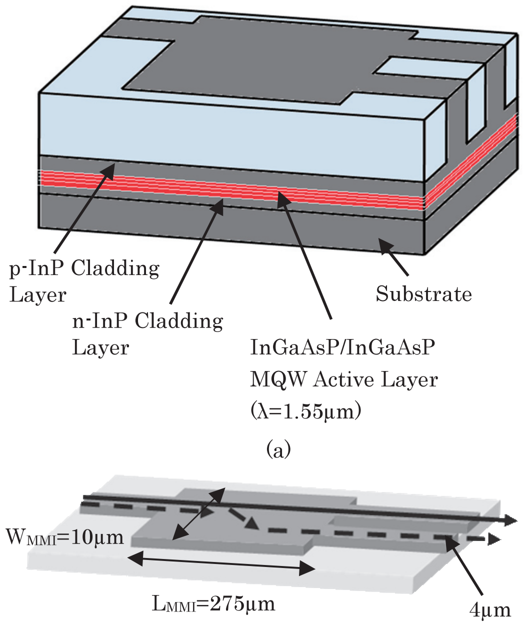
$$W_e \approx W_{MMI} + (\frac{\lambda}{\pi})(\frac{n_c}{n_r})^{2\sigma}(n_r^2 - n_c^2)^{\frac{1}{2}} \qquad (2)$$

$$L_{MMI} \approx \frac{4n_r W_e^2}{3\lambda} \qquad (3)$$

$$L_{MMI} = \frac{M}{N} 3L_{\pi} \qquad (4)$$

where, W_e is the MMI effective width, σ=0 for TE and σ=1 for TM, L_{π} is the beat length of the two lowest-order modes, and M=1 for shortest possible MMI length and N is set to 4 as we positioned the access port at distance $W_e/4$ from the edge of MMI region[14, 17]. As a result, the L_{MMI} and W_{MMI} were designed to be 275μm, 10μm, respectively. Figure 3 illustrates the schematic views of the designed novel active-MMI BLD explained in the above.

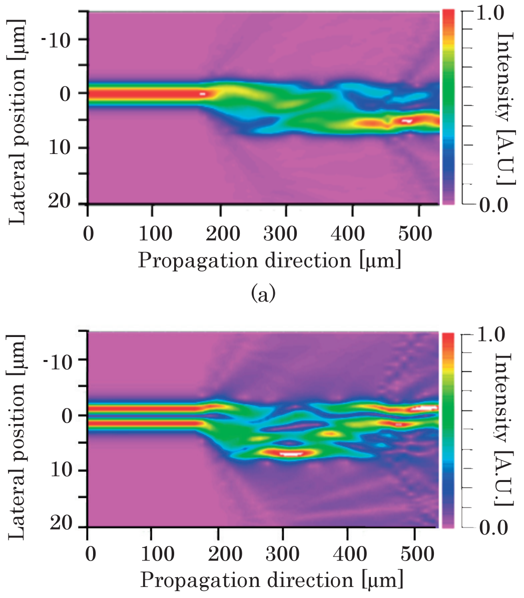
Figure 4 (a) and (b) show the simulated results of the novel two different identical propagation paths. As can be seen in these figures, 0th-order mode propagates toward cross-port while 1st-order mode propagates toward bar-port. Therefore, we could confirm that the properly designed MMI structure supported two identical propagation paths with depending on the propagation mode-order[18, 19]. As the single-port side is fully shared by the two propagation paths in addition to the co-relation area inside of the MMI region, sufficient cross-gain region can be achieved.



(a)

(b)

Fig. 3 Schematics of the active-MMI BLDs. (a) Perspective layer structure, and (b) waveguide geometry.

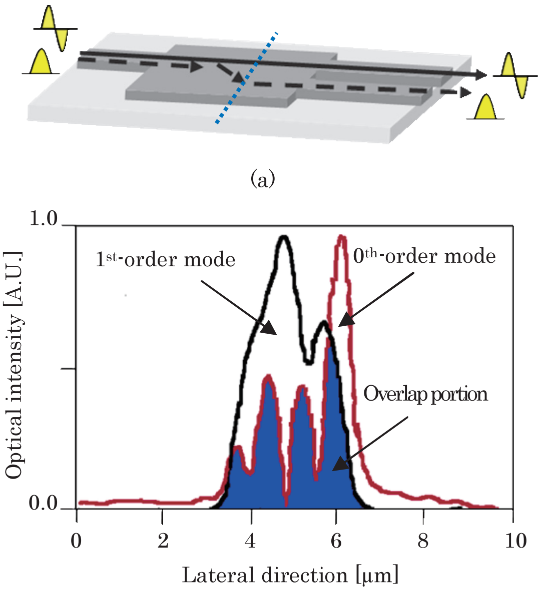


(a)

(b)

Fig. 4 Two identical propagation paths in novel active-MMI waveguide structure. (a) 0th-order mode, and (b) 1st-order mode.

Next, we estimate the overlap portion of the actual optical field profile between these two propagation modes in the design explained in the above.



(a)

(b)

Fig. 5 Optical field profiles in the novel active-MMI waveguide area. (a) Propagation paths of 0th-order and 1st-order modes light, (b) optical of field profiles corresponding to the position indicated in (a) (blue dotted line). The blue colour indicates overlap portion of the optical field profiles in the MMI region.

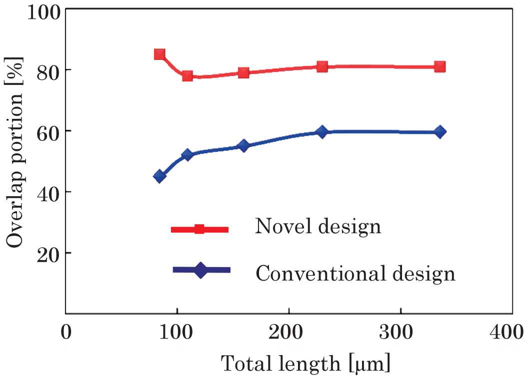
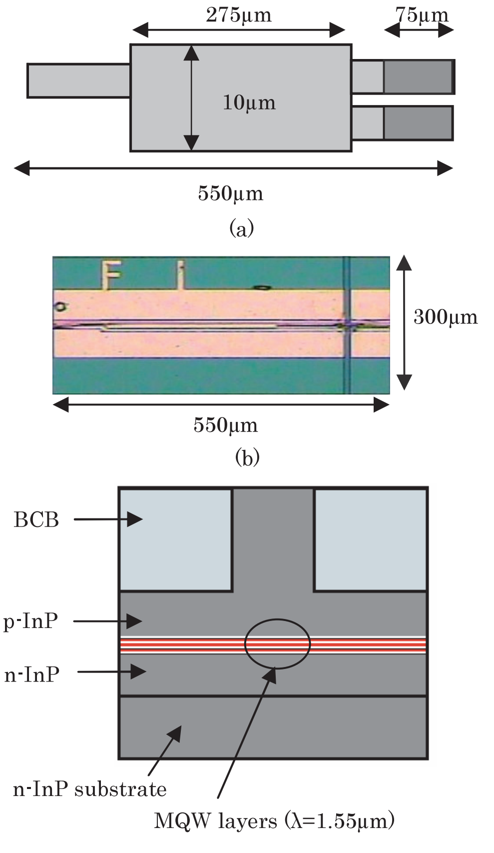


Fig. 6 The overlaps of the two identical propagation paths for the novel active-MMI BLDs and for the previously reported symmetric active-MMI BLDs.

Figure 5 (b) shows one example of the optical field profile for the both 0th-order (black line) and 1st-order (red line) modes within the MMI area while blue colour indicates the overlap portion of the optical field profiles in the MMI region at a certain position (see Fig. 5 (a)). In order to calculate the overlap portion of the optical field profiles for the two identical propagation paths along the whole MMI region, we calculated the overlap portion of the optical filed profiles at every 5µm along the whole MMI area. The overlap portion of the optical field profiles in the MMI region and in the shared access port (left had-side in Fig. 5 (a)) was estimated to be more than 80%, while the one in the case of previously reported symmetric active-MMI BLD was 50%. Figure 6 shows the estimated overlap portion of the optical field profiles for the novel active-MMI BLDs and the previously reported symmetric active-MMI BLDs as a function of their total device length. As is shown here, we can see that the novel active-MMI BLDs can preserve larger overlap portion of the optical field profiles (more than 80%) even for a device length below 100µm. This clearly proves the potential of the novel active-MMI BLDs for the future highly integrated optical bit-memory elements for RAM application.

4. Results and Discussion



(a)

(b)

(c)

Fig. 7 Fabricated novel active-MMI BLDs. (a) Top schematic, (b) top microscopic view, and (c) layer structure.

Figure 7 shows the fabricated novel active-MMI BLDs. As is explained in section 3, the access width was set to be 4µm, which was designed so as to support the 0th-order and 1st-order modes while it cut off the 2nd-order mode. InGaAsP/InGaAsP multiple quantum well (7 layers, λ=1.55µm) was used for the active layer. MMI region was designed to have a width of 10µm and a length of 275µm. Total length of the fabricated devices was 550µm including saturable absorber section of 75µm. For the actual fabrication, MOVPE (metal-organic vapor phase epitaxy) was used for crystal growth, and then RIE (reactive ion etching) was used for structuring waveguides. To realize precisely designed MMI geometries, i-line stepper was used for the lithography technique.

The fabricated active-MMI BLDs were mounted on AIN heat sinks as junction-up and the temperature was set at 25°C using thermo-electric cooler. Figure 8 shows the power-current (P-I) characteristic[8, 20, 21]. As can be seen in the figure, relatively low operation current of 100mA, with relatively wide hysteresis window of 8mA, compared to the conventional scheme[6], have been achieved successfully. This might be due to the effect of the large cross-gain saturation region between 0th-order and 1st-order modes, as the saturable absorber length was set to be only 75µm length. Moreover, high optical ON/OFF ratios of 17dB

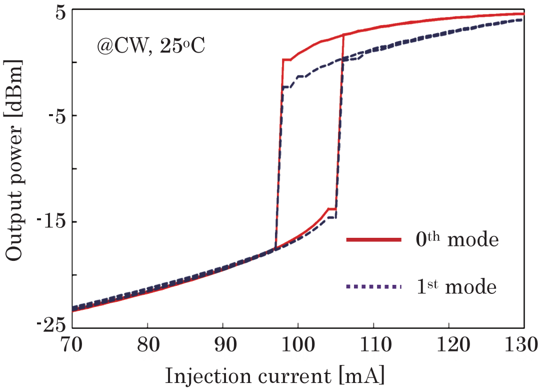


Fig. 8 P-I characteristics of the fabricated novel active-MMI BLDs(@CW, 25°C).

Fig. 9 Near-field-pattern of the fabricated novel active-MMI BLDs.

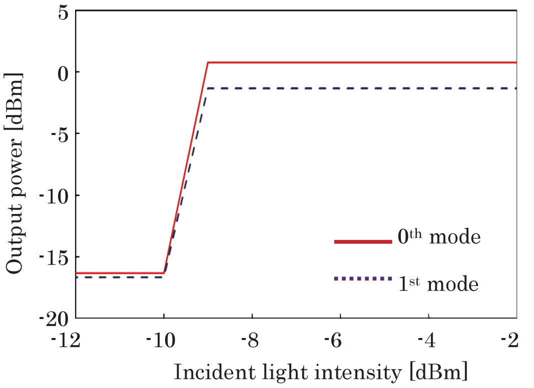


Fig. 10 Bit-memory switching characteristic. The operation current was 100mA, and the wavelength of the injected light was 1.55μm.

for 0th-order mode and 15dB for 1st-order mode were confirmed for the fabricated novel active-MMI BLDs.

We also investigated near-field-patterns of the fabricated devices in ON state for the both 0th-order and 1st-order modes. Figure 9 shows the near-field-pattern of the actually implemented novel active-MMI BLDs at an injection current of 110mA. As can be seen in the figure, 0th-order and 1st-order modes can be recognized and distinguished clearly.

For the evaluation of the bit-memory characteristics, the operation current of 100mA was injected to the fabricated devices, and then CW light of 1550nm (TE mode) was used as an injection light for the memory operation. Figure 10 shows the bit-memory switching characteristic of the fabricated novel active-MMI BLDs. As can be seen in the figure, the minimum switching power of only -9dBm was achieved for the actual turning on the bit-memory element. We hope that this novel principle will contribute to realize highly integrated optical bit-memory element for RAM application in the future.

5. Summary

A novel principle of active-MMI BLD, utilizing cross-gain saturation between the 0th-order and 1st-order modes, has been proposed and demonstrated. BPM simulation results predict the large overlap portion of the optical field profiles for cross-gain saturation than that of the previously reported symmetric active-MMI BLD. The demonstrated performances of the device exhibit optical bi-stability at 100mA operation current with hysteresis window width of 8mA in relatively short cavity of only 550μm. Moreover, the 0th-order and 1st-order modes were switched with sufficiently high optical ON/OFF ratio of more than 15dB. We hope that this novel principle will contribute to realize highly integrated optical bit-memory element for RAM application in the future.

Acknowledgement

A part of this work was supported by NICT, Japan.

References

1) 2008 WHITE PAPER information and communications in Japan http://www.johotsusintokei.soumu.go.jp/whitepaper/ja/h20/index.html

2) http://innovation.nikkeibp.co.jp/etb/20060417-00.html

3) W. D'Oosterlinck, J. Buron, F. Öhman, G. Morthier, and R. Baets, "All-optical flip-flop based on an SOA/DFB-laser diode optical feedback scheme", IEEE Photonics Technology Letters, Vol. 19, No. 7, pp. 489-491 (2007)

4) M. T. Hill, H. J. S. Doreen, T. Vriles, X. J. M. Leijtens, J. H. Besten, B. Smalbrugge, Y. S. Oel, H. Blnsma, G. D. Khoe, and M. K. Smit, "A fast low-power optical memory based on coupled micro-ring lasers", Nature, Vol. 432, No. 7014, pp. 206-209 (2004)

5) R. Clavero, F. Ramos, and J. Marti, "All-optical flip-flop based on an active Mach-Zehnder interferometer with a feedback loop", Optical Letters, Vol. 30, No. 21, pp. 2861-2863 (2005)

6) M. Takenaka, and Y. Nakano, "Multimode interference bistable laser diode", IEEE Photonics Technology Letters, Vol. 15, No. 8, pp. 1035-1037 (2003)

7) M. Takenaka, M. Raburn, and Y. Nakano, "All-optical flip-flop multimode interference bistable laser diode", IEEE Photonics Technology Letters, Vol. 17, No. 5, pp. 968-970 (2005)

8) H. A. Bastawrous, H. Saikaku, H. Jiang, Y. Tahara, S. Matusuo, and K. Hamamoto, "A novel active MMI bi-stable laser using cross gain saturation between fundamental and first order modes", Proceedings of The 34th European Conference on Optical Communication (ECOC 2008, Brussels, Belgium), Vol. 5, P.2.15, pp. 81-82 (2008).

9) K. Hamamoto, J. De Merlier, M. Ohya, K. Shiba, K. Naniwae, S. Sudo, and T. Sasaki, "First demonstration of novel active multi-mode interferometer (MMI) LDs integrated with 1st order-mode permitted waveguides", IEICE Electronics Express, Vol. 2, No. 13, pp. 399-403 (2005)

10) K. Hamamoto, E. Gini, C. Holtmann and H. Melchior, "Single transverse mode active MMI InGaAsP/InP laser diode", Electronics Letters, Vol. 34, No. 5, pp. 462-464 (1998)

11) K. Hamamoto, "Recent progress of opto-electronics devices by using multi-mode interference (MMI)", IEICE Transactions on Electronics (Japanese Edition), Vol. J89-C, No. 6, pp. 365-371 (2006)

12) Y. Chung and N. Dagli, "An assessment of finite difference beam propagation method", IEEE Journal of Quantum Electronics, Vol. 26, No. 8, pp. 1335-1339 (1990)

13) C. L. Tang, A. Schremer, and T. Fujita, "Bistability in two-mode semiconductor lasers via gain saturation", Applied Physics Letters, Vol. 51, No. 18, pp. 1392-1394 (1987)

14) J. Leuthold, J. Eckner, E. Gamper, P. A. Besse, and H. Melchior, "Multimode interference couplers for the conversion and combining of zero and first order modes", Journal of Lightwave Technology, Vol. 16, No. 7, pp. 1228-1239 (1998)

15) K. Okamoto, "Wave theory of optical waveguides", in Fundamentals of optical waveguides, Ch. 1, Academic Press (2000)

16) Y. Kokubun, "Semiconductor optical waveguides", in Handbook of semiconductor lasers and photonic integrated circuits, Edited by Y. Suematsu and A. R. Adams, Ch. 3, Chapman and Hall (1994)

17) L. B. Soldano, E. C. M. Pennings, "Optical multi-mode interference devices based on self-imaging: principles and applications", Journal of Lightwave Technology, Vol. 13, No. 4, pp. 615-627 (1995)

18) H. Saikaku, H. A. Bastawrous, and K. Hamamoto, "Theoretical researches in the principle of optical RAM for next generation all optical routers", Extended Abstracts of The 68th Autumn Meeting, The Japan Society of Applied Physics, No. 3, 6a-C-4, pp. 1154 (2007)

19) H. A. Bastawrous, H. Saikaku, and K. Hamamoto, "Preliminary research on a novel principle of optical memory based on MMI", Proceedings of The 2007 IEICE Society Conference, No. 3, C-3-27, pp. 150 (2007)

20) H. Jiang, H. A. Bastawrous , H. Saikaku, Y. Tahara, S. Matusuo, and K. Hamamoto, "Optical RAM based on bi-stability between different lateral modes", Extended Abstracts of The 69th Autumn Meeting, The Japan Society of Applied Physics, No. 3, 2p-P3-6, pp. 1020 (2008).

21) H. Jiang, H. A. Bastawrous, H. Saikaku, Y. Tahara, S. Matsuo, and K. Hamamoto, "Optical random access memory (RAM) based on bi-stability between different lateral modes using novel active multi-mode-interferometer (MMI)", Record of 2008 Joint Conference of Electrical and Electronics Engineers in Kyushu (IEEE-Kyushu section), 03-1P-09 (2008)