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Published in:
Proceedings of the European Conference on Optical Communication (ECOC) 2011

Publication date:
2011

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):

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High-Speed and Low-Energy Flip-Flop Operation of
Asymmetric Active-Multimode Interferometer
Bi-Stable Laser Diodes

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Abstract: High-speed (121/25 ps rise/fall time) and low-switching energy (7.1 and 3.4 fJ) all-
optical flip-flop operation of single-wavelength high-mesa asymmetric active-MMI bi-stable laser
diodes is demonstrated for the first time using 25 ps long switching pulses.
OCIS codes: (130.0250) Opto-electronics; (130.4815) Optical switching devices

1. Introduction

To reduce the huge amount of electrical power consumed at current network routers due to optical-to-electrical-to-
optical (OEO) conversion [1], one possible solution is to realize all-optical routers. Optical random access memory
(RAM) is a key functionality in such all-optical routers. So far, several optical memory elements have been
proposed as all-optical memory [2-9]. Recently, we have demonstrated high-mesa waveguide structure asymmetric
active-multimode interferometer bi-stable laser diodes (MMI BLDs) [5]. The implemented devices showed a wide
hysteresis window, which is an important feature of future highly integrated RAMs [6], together with superior
single-wavelength emission (without using grating structures) [5]. However, in order to establish the full potential
of this technology, it is essential to demonstrate high speed operation compatible with multi-gigabit per second
signals.

In this work, we demonstrate the high speed response of high-mesa asymmetric active-MMI BLDs for the first
time. All-optical flip-flop switching is achieved with 25 ps long pulses. The implemented devices showed fast rise
and fall times of 121 ps and 25 ps, respectively. Furthermore, the required set and reset pulse energies were only
7.1 fJ and 3.4 fJ, respectively.

2. Concept and Design

The bi-stability of the active-MMI BLDs is mainly based on cross-gain saturation between two identical
propagation paths in the same cavity. Extremely wide hysteresis windows have been realized utilizing the bi-
stability of the lowest two lateral mode paths (0th order mode path, and 1st order mode path) in the asymmetric
active-MMI configuration, as shown in Fig. 1 (a) [7-9]. Moreover, we have utilized high-mesa for the waveguide
structure which has shown single-wavelength emission with side mode supression ratio (SMSR) of 30 dB [5]. To
further decrease the threshold current, a saturable absorber (SA) region with a length of only 25 µm was
implemented in the device used in this work. The length portion of the cross-gain saturation region between the two

Fig 1. Schematic view of high-mesa asymmetric active-MMI BLDs. (a) Waveguide configuration, (b) cross-section.
propagation paths was increased to approximately 80% to maintain a sufficiently large hysteresis window with such a short saturable absorber design [7].

The implemented asymmetric active-MMI BLDs had a cavity length of $L=315 \mu m$ (including 25 $\mu m$ length SA region). The MMI region width and length were 8$\mu$m and 138$\mu$m, respectively. The access waveguide width was set to be 3 $\mu$m. They were realized in high-mesa waveguide structure as shown in Fig. 1 (b). We used InGaAsP/InGaAsP multiple quantum wells ($\lambda=1.55 \mu m$) as in [5]. The InGaAsP/InGaAsP multiple quantum wells were grown by metal–organic vapor phase epitaxy (MOVPE) on an InP substrate. To realize precisely the designed MMI geometries, an i-line stepper was used for the lithography technique. The structure was etched down using reactive ion etching (RIE) to fabricate the high-mesa waveguide.

3. Results and discussion

Fig. 2 (a) shows the power-current (P-I) characteristics of the implemented devices. It can be seen that, a low hysteresis threshold $I_{th}$ of 60 mA, and a wide hysteresis window $\Delta I_{hys}$% (defined as the percentage ratio of the hysteresis window width to the lower hysteresis threshold) of 15% could be obtained. This was made possible thanks to the increase of the cross-gain region to reach 80% of the total device length. From this result, it was confirmed that high-mesa waveguide structure asymmetric active-MMI BLDs can achieve sufficiently large hysteresis windows with relatively low threshold current. Fig. 2 (b) shows the emission spectrum in the “on” state. Remarkable single wavelength emission performance, based solely on the active-MMI phenomena, has been successfully obtained at a wavelength of $\lambda=1549$ nm, with a side-mode suppression ratio of 25 dB.

![Fig. 2. Characteristics of the implemented devices. (a) Power-current characteristics and (b) emission spectrum in the “on” state of the implemented devices.](image)

In order to investigate the dynamic memory operation, light pulses at $\lambda=1549$ nm, which was the lasing wavelength, were injected for off-to-on switching and light pulses at $\lambda=1554$ nm, which was different from lasing wavelength, were used for on-to-off switching. Fig. 3 shows the experimental setup for the measurement of the dynamic behavior of the all-optical flip-flops. The pulses were generated from a 40 Gbit/s bit-pattern generator and had a duration of 25 ps. A fiber delay line was used to introduce a delay between the set and reset pulses. The results are shown in Fig. 4. It can be seen that the high-mesa asymmetric active-MMI BLDs could realize all optical flip-flop switching using 25 ps pulses. Furthermore, the switching energies of the set and reset pulses were only 7.1 fJ and 3.4 fJ respectively. Fast rise and fall times were also recorded for the devices. The evaluated rise and fall-times were 121 ps and 25 ps, respectively (see Fig. 4 (c), and (d)), despite the fact that the devices were carrier injected bi-stable laser diodes.

4. Conclusion

We have successfully demonstrated all-optical flip-flop operation of high-mesa asymmetric active-MMI BLDs using 25 ps long pulses. The devices showed very fast rise and fall times of 121 ps and 25 ps, respectively, with low...
set and reset pulse energies of 7.1 fJ and 3.4 fJ, respectively. We expect the potential of asymmetric active-MMI BLDs can be exploited in future all optical routers.

This work was supported in part by NICT, Japan.

**Fig. 3.** Experimental setup for the measurement of the dynamic behavior of the all-optical flip-flops.

**Fig. 4.** Dynamic memory operation of high-mesa asymmetric active-MMI BLDs using 25 ps switching pulses. (a) Set and reset pulses, as well as device output, (b) rise time and (c) fall time characterisation.

**References**