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Abstract: We demonstrate fast and low energy all optical flip-flop devices based on asymmetric active-multimode interferometer using high-mesa waveguide structure. The implemented devices showed high speed all-optical flip-flop operation with 25ps long pulses. The rising and falling times of the output signal were 121 ps and 25 ps, respectively. The required set and reset pulse energies were only 7.1 fJ and 3.4 fJ, respectively.

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1. Introduction

The amount of network data-traffic keeps increasing at an annual rate of 40% in Japan, to a large extent due to the increase in the amount of video information transmitted over the internet [1-2]. The electrical power consumption of network routers in Japan was estimated to be 8 billion kWh in 2006 and is forecasted to continue increasing in proportion to the expansion of network traffic [1-2]. A significant fraction of the power consumed at current network routers is due to optical-to-electrical-to-optical (OEO) conversion. To solve this issue, one possible solution is to realize all-optical routers that can potentially lead to energy savings. All-optical flip-flops offer one of the key functionalities for such all-optical routers since they can act as optical random access memory (RAM) elements.

So far, several types of all-optical flip-flops have been proposed and demonstrated as all-optical memory elements, including active multi-mode interference (MMI) [3] bi-stable laser diodes (BLDs) [4-8], coupled laser diodes [9], semiconductor optical amplifier-based Mach-Zehnder interferometers [10], distributed feedback lasers with continuous-wave (CW) light injection [11-12], polarization-bi-stable vertical-cavity surface-emitting lasers (VCSELs) [13], etc. Among them, active-MMI BLDs are attractive due to their relatively superior fabrication tolerance and their ability to achieve low threshold currents with wide hysteresis windows, which are important features of future highly integrated RAMs [4].

We have proposed and demonstrated high-mesa waveguide structure asymmetric active-MMI BLDs without any grating or other additional structure [5]. The implemented devices showed a wide hysteresis window, together with superior single-wavelength emission (λ= 1556 nm, side-mode suppression ratio SMSR= 30 dB, without using grating structures) [14], and achieved all optical bi-stable switching operation [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 experimentally the high speed response of high-mesa asymmetric active-MMI BLDs for the first time. All-optical flip-flop switching was 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 active-MMI BLDs is mainly based on cross-gain saturation between two identical propagation paths in the same cavity [15-16]. Extremely wide hysteresis windows have been realized by utilizing the bi-stability of the lowest two lateral mode paths (0th and 1st order mode paths) in asymmetric active-MMI configurations, as shown in Fig. 1(a) [16-17].

We utilized high-mesa for the waveguide structure. The very high contrast in the refractive index of the high-mesa structure compared to regular ridge and/or buried-

heterostructures helps to achieve "sharp focus" in the self-imaging of active-MMIs [18]. As the active-MMI phenomenon requires coherence, high-mesa with asymmetric active-MMI results in single wavelength emission, namely "interference in the longitudinal mode" [18]. Implemented devices of this type have shown single-wavelength emission with a SMSR of 30 dB [5]. Furthermore, all-optical bi-stable switching operation was confirmed successfully using different wavelengths fort the set and reset light pulses.
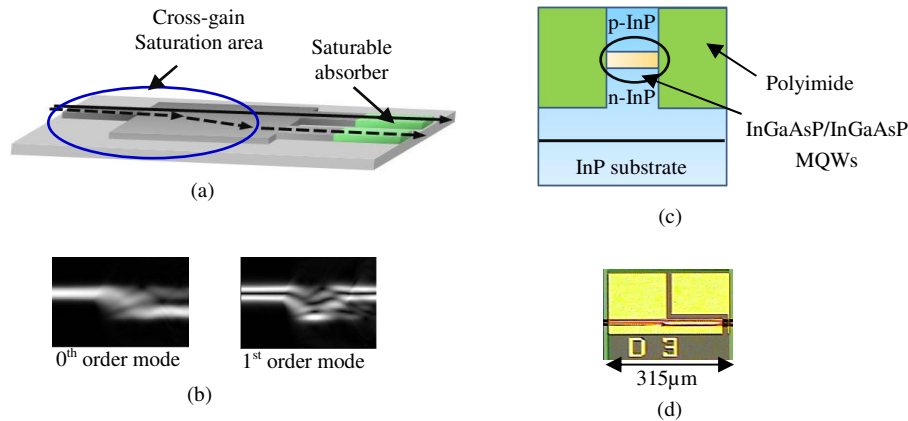
Fig. 1. Schematic view of high-mesa asymmetric active-MMI BLDs. (a) Waveguide configuration. (b) Simulated (using the beam propagation method, BPM) optical of the two propagation paths. (c) Cross-sectional representation of the structure. (d) Top view of the fabricated device.

To further decrease the threshold current, a saturable absorber (SA) region with a length of only 25 μm was implemented in this work. The length portion of the cross-gain saturation region between the two propagation paths was increased to approximately 80% to maintain a sufficiently large hysteresis window with such a short saturable absorber design [15].

The implemented asymmetric active-MMI BLDs had a cavity length of L= 315 μm (including the 25 μm long SA region). The MMI region width and length were 8 μm and 138 μm, respectively. The access waveguide width was set to be 3 μm. They were realized in high-mesa waveguide structures, as shown in Fig. 1(c). We used InGaAsP/InGaAsP multiple quantum wells (λ=1.55 μm) as in [5]. The 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. As can be seen in Fig. 1(d), the high-mesa waveguide structure asymmetric active-MMI BLDs were fabricated on a single compact chip, with no refection coatings.

3. Experimental results

3.1. Static characteristics

Fig. 2 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 realized even in high-mesa waveguide structures. This was made possible thanks to the increase of the cross-gain region to reach 80% of the total device length, with a short saturable absorber length of only 25 µm. 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 currents. Fig. 3(a) and Fig. 3(b) show the

emission spectrum and near-field-pattern in the "on" state, respectively. Remarkable single wavelength emission performance, based solely on the active-MMI phenomena, has been successfully obtained at a wavelength of λ= 1549 nm, with a side-mode suppression ratio of 25 dB.
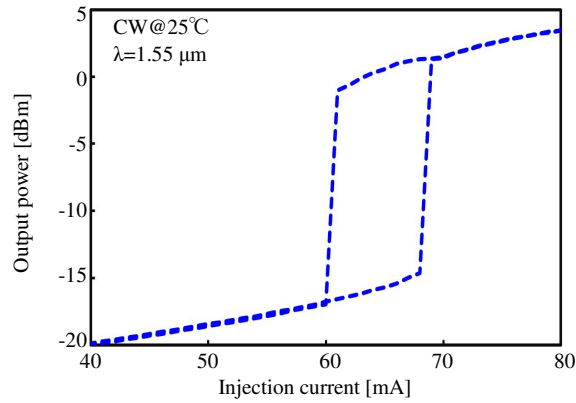

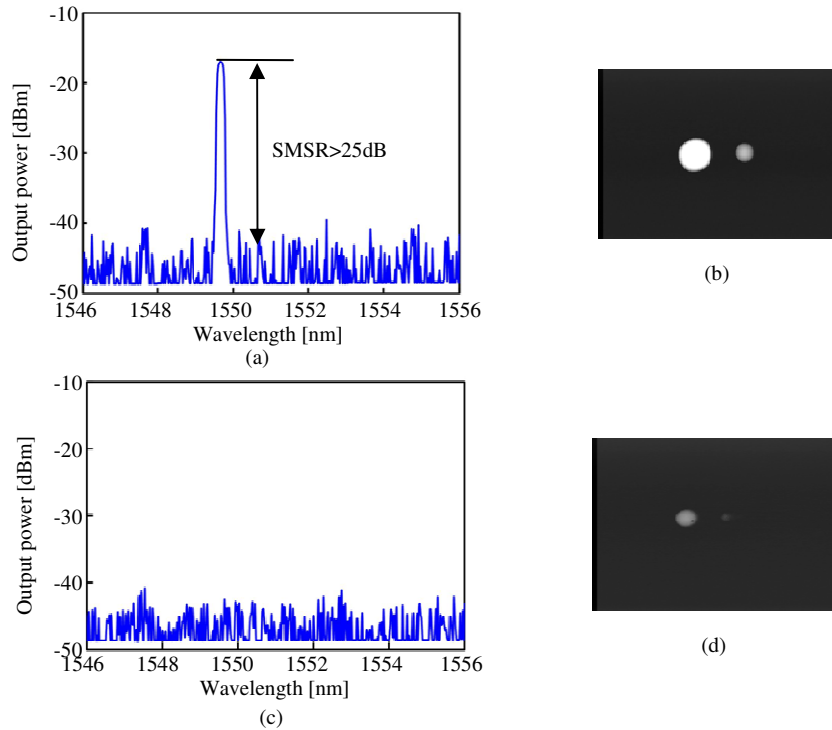Fig. 2. Power-current characteristics of the implemented device.

Fig. 3. Emission spectra and near-field-patterns of the implemented device in the "on" and "off" states. (a) Emission spectrum in the "on" state, (b) near-field-pattern in the "on" state, (c) emission spectrum in the "off" state and (d) near-field-pattern in the "off" state.

In order to investigate the memory operation, a current of 65 mA was injected to the implemented device, a CW light at 1549 nm was used as the set light, and a CW light at a different wavelength of 1554 nm was used as the reset light. The device shows bi-stable

switching behavior by injection of the set and reset light. The minimum set and reset switching light power levels were -21 dBm and -24 dBm, respectively. Fig. 3(c) and Fig. 3(d) show the emission spectrum and near-field-pattern in the "off" state. In the un-centered MMI configuration, not only lateral modes, but also longitudinal modes interfere. When the set light is injected, corresponding to the 0th order mode lasing light in the implemented device, the device is switched to the "on" state due to cross-gain saturation. When the reset light is injected, corresponding to the 1st order mode lasing light, the 0th order mode light is switched off. Taking into account the fact that the access waveguide is nearly close to the 1st order mode cut-off width, and that this waveguide width is not sufficient for 1st order mode emission at low injection currents (as shown Fig. 3(a)) [5], the 1st order mode cannot be excited and the device switches to the "off" state.

3.2. Flip-flop operation set-up

The set-up used for dynamic flip-flop demonstration is shown in Fig. 4. Two continuous-wave tunable lasers at 1549 nm and 1554 nm were used as the signal sources. The optical data pulses were created by simultaneously modulating the two CW lights in a single Mach-Zehnder intensity modulator driven from a 40 Gbit/s bit pattern generator. The two wavelengths were further separated into set and reset signals by an arrayed waveguide grating. The losses of the modulator were compensated using an erbium-doped fiber amplifier (EDFA). Attenuators were used to control the energy of the set and reset pulses independently. We used an optical delay line to create an adjustable delay between the set and reset pulses. The set and reset pulses were injected into the asymmetric active-MMI BLD through circulators and a piece of lensed fiber. The output signal from the asymmetric active-MMI BLD was extracted through the optical circulator and monitored with a digital sampling oscilloscope.
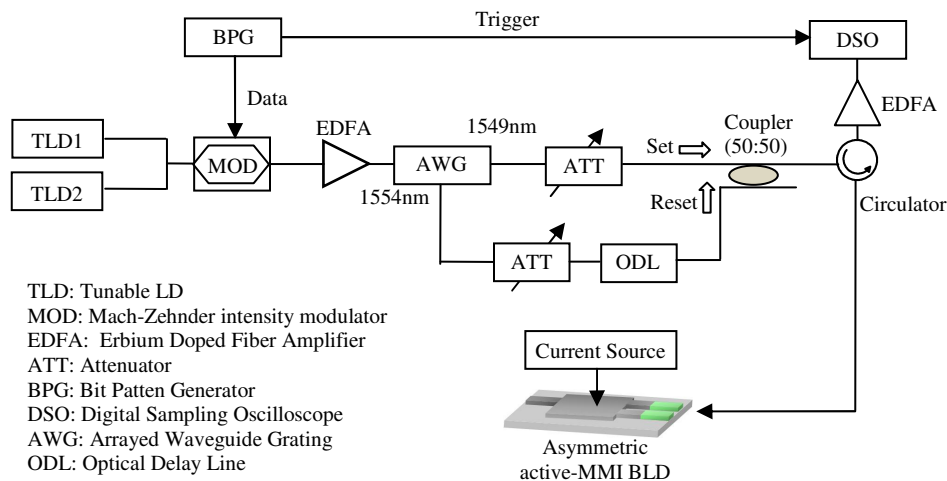

TLD: Tunable LD
MOD: Mach-Zehnder intensity modulator
EDFA: Erbium Doped Fiber Amplifier
ATT: Attenuator
BPG: Bit Patten Generator
DSO: Digital Sampling Oscilloscope
AWG: Arrayed Waveguide Grating
ODL: Optical Delay Line

Fig. 4. Experimental setup for the measurement of the dynamic behavior of the all-optical flip-flops.

3.3. High speed flip-flop operation

The flip-flop operation results obtained with this set-up are shown in Fig. 5. Light pulses at λ= 1549 nm, which was the lasing wavelength, were injected for off-to-on switching, while light pulses at λ= 1554 nm, which was different from the lasing wavelength, were used for on-to-off switching. The duration of the set and reset pulses was 25 ps. The reset pulses were

delayed 1.6 ns by the fiber delay line. 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 device. The evaluated rise and fall-times were 121 ps and 25 ps, respectively (see Fig. 5 (b), and (c)), despite the fact that the device was a carrier injected bi-stable laser diode. The "on" switching is based on lasing, which involves conversion of injected current into photons, but the "off" switching does not require this procedure. This is the reason for the rise time being significantly longer than the fall time. As shown in Fig. 5(b), relaxation oscillations induced an over-shoot on the rising edge of the generated optical signal. Reducing the device total size and utilizing reflective coatings may result in a shorter rise time. The memory has therefore been shown to react to signal pulses as short as 25 ps. Therefore, we think that the device could be exploited for high-speed packet routing. For such applications, the required switching speed should be compatible with the packet duration (possibly of the order of a few hundred nanoseconds), as opposed to bit-by-bit switching that would be required for logical operations.
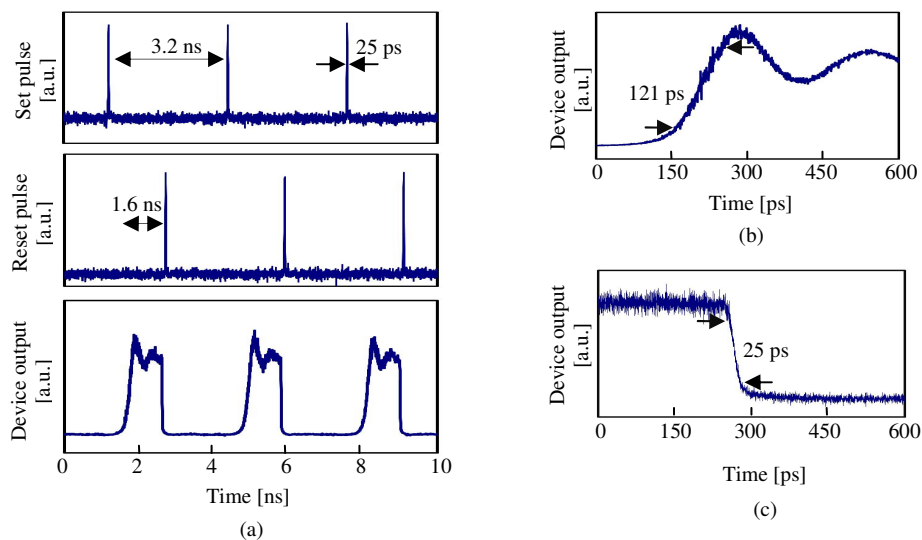

Fig. 5. Dynamic memory operation of the high-mesa asymmetric active-MMI BLD using 25 ps switching pulses. (a) Set and reset pulses, as well as device output waveform, (b) rise time and (c) fall time characterisation.

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 that such asymmetric active-MMI BLDs have the potential to be exploited in future all optical routers.

Acknowledgments