Fast all-optical flip-flop based on a single distributed feedback laser diode

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Abstract: Since there is an increasing demand for fast networks and switches, the electronic data processing imposes a severe bottleneck and all-optical processing techniques will be required in the future. All-optical flip-flops are one of the key components because they can act as temporary memory elements. Several designs have already been demonstrated but they are often relatively slow or complex to fabricate. We demonstrate experimentally fast flip-flop operation in a single DFB laser diode which is one of the standard elements in today's telecommunication industry. Injecting continuous wave light in the laser diode, a bistability is obtained due to the spatial hole burning effect. We can switch between the two states by using pulses with energies below 200 fJ resulting in flip-flop operation with switching times below 75 ps and repetition rates of up to 2 GHz.

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1. Introduction

New upcoming internet-based services (such as video-based multimedia, fast peer-to-peer file transfer, ...) generate an increasing traffic load. The implementation of optical fibers as a

transport medium for high bit-rate data signals increases the speed of telecommunication significantly. However, the electronic data processing of these signals imposes a severe bottleneck and all-optical processing techniques will be required in the future [1]. Therefore, more and more attention is drawn to all-optical packet-switched networks where packets of data are routed all-optically through the network based on the information contained in the header. All-optical flip-flops offer one of the key functionalities since they can act as optical memory elements and store the header information while the payload is routed to the right output port [2, 3].

All-optical flip-flops are generally based on a bistability with the ability to switch between the two different states using short optical pulses. Many of the designs that have been proposed so far are based on the nonlinear behaviour in the gain: coupled laser diodes [4, 5], multimode interferometers [6], SOA-based Mach-Zehnder interferometers with a feedback loop [7], ... However, most of these designs are relatively complex or require a difficult active passive integration. The switching times are in general rather long: most devices need at least 150 ps, only the coupled micro-rings [5] have a switching time of 15 ps.

There has been already research on bistability in distributed feedback (DFB) laser diodes. A two-segmented DFB laser diode has been demonstrated as all-optical flip-flop [8]: the first segment is biased under threshold and is acting as a saturable absorber, while the second segment provides the gain. However, due to the slow carrier recovery time of the laser the repetition frequency was limited to several hunderds of megahertz. Dispersive bistabilities in DFB amplifiers have also been used to achieve flip-flop operation [9], but they require a very tight wavelength control and have no fast switch-off.

Here we demonstrate experimentally all-optical flip-flop operation using a single DFB laser diode [10]. As will be explained in the next section, we can obtain a bistability by injecting continuous wave (CW) light into the DFB laser. This bistability can be applied to obtain flip-flop operation using short optical pulses on both sides of the laser diode.

2. Concept

Distributed feedback laser diodes are one of the standard elements in telecommunication because of their small linewidth. The feedback in such laser diodes is not localized at the facets, but is distributed throughout the cavity because of diffraction by a Bragg grating. When we inject light outside the stopband of the grating, the laser diode will act as an amplifier without feedback.

Under injection of CW light, we can distinguish between two different stable states: one in which the laser is lasing and another one where it is switched off. When the laser is lasing, the gain will be clamped and relatively small. Therefore, the injected light experiences only a small amplification and has almost no influence on the laser light. In the second state on the other hand, the laser is switched off and the injected light experiences a high amplification. This results in a rising power progression throughout the cavity and therefore a non-uniform distribution of the carriers (Fig. 1(a)). This effect is known as spatial hole burning. The non-uniformity of the carriers will affect the refractive index, thus leading to a distortion of the Bragg reflections in the laser diode. The losses inside the cavity will become higher and the threshold for lasing will rise. Eventually the laser will stay switched off. The two states are equally possible for a range of input powers of the injected light and we obtain a bistability in the lasing power (Fig. 1(b)). The simulations of Fig. 1 were done using a commercial software package [11].

We can exploit the bistability to obtain flip-flop operation by injecting short optical pulses as illustrated in Fig. 2. To make the device operative in the bistable regime, CW power is injected into the DFB laser. A pulse injected at the same side as the CW light will move the DFB laser out of the hysteresis curve and will switch off the laser. To switch the laser on again, a pulse is injected from the other side, since this will restore the uniformity of the carrier distribution.
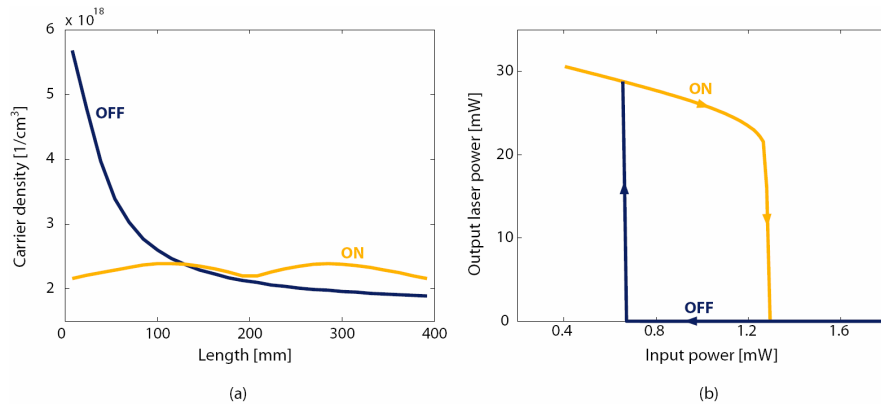
Fig. 1. (a) The longitudinal distribution of the carriers for the two different states in a $\lambda/4$-shifted DFB laser with length 400 µm, AR-coatings and κL-value of 1.2; (b) Simulation of the laser power as a function of the injected light.

Fig. 2. Illustration of the concept for all-optical flip-flop operation.

3. Bistability

For the experiments we used a $\lambda/4$-wave shifted distributed feedback laser with a length of 400 µm and a κL-value of 1.6. The laser diodes need an accurate antireflective coating, otherwise backward reflections destroy the effect of the spatial hole burning. Therefore, we use laser diodes with a reflectivity of 10^{-4} at both facets. The laser has a threshold current of approximately 30 mA and emits light at 1553 nm.
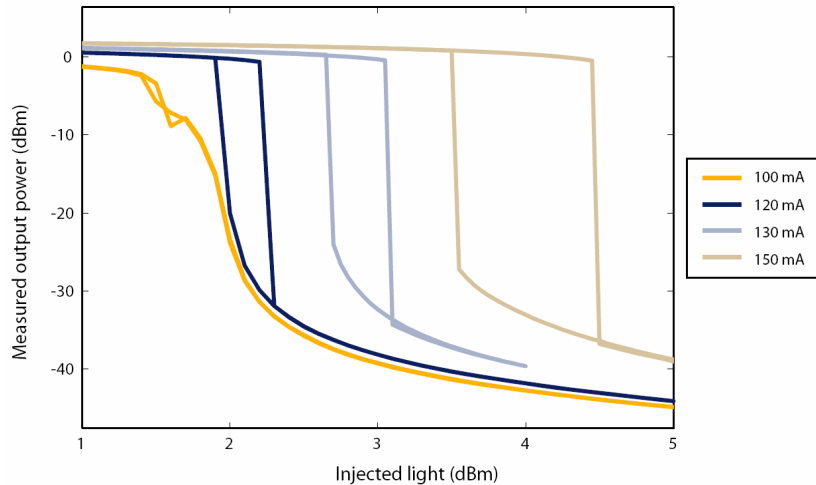

Fig. 3. The measured hysteresis for different injection currents.

We inject CW-light at a wavelength of 1543 nm into the DFB laser. An attenuator is used to sweep the power of the injected light. The fiber-to-chip coupling is done by means of a lensed fiber. An optical band-pass filter separates the light of the DFB laser diode from the

CW power. The hysteresis curve is measured for different values of the injection current and is shown in Fig. 3.

We observe that for higher currents, the hysteresis curve widens and shifts to higher input powers. This can be partly explained by the increased stability of the laser operation at higher currents. The shift of the lower boundary of the hysteresis with current may be due to heating and increased nonradiative recombination. For a current of 120 mA, we need about 2 mW of CW power to work in the bistable regime (before the coupling with the lensed fiber).

4. Flip-flop operation

4.1. Set-up

To demonstrate the flip-flop operation, we use the set-up depicted in Fig. 4. To provide and control the CW power, a wavelength tunable laser is used followed by an attenuator. The light from another tunable laser is sent through a modulator to generate the set and reset pulses. The modulator is driven by a NRZ-bit pattern generator which creates pulses of approximately 100 ps length. These are split through a 3 dB coupler resulting in identical set and reset pulses. Using erbium-doped fiber-amplifiers (EDFA), we compensate for the losses of the modulator and the coupler. Attenuators are used to control the energy of the set and reset pulses separately. The set-pulses are injected on the right-hand side of the DFB laser after passing through an optical bandpass filter to eliminate noise generated by the EDFA. Polarization wheels are used to control the polarization of the injected light. On the left-hand side we use another 3 dB coupler to combine the CW-light with the reset pulses. Small changes in the repetition rate allow us to vary the delay between the set and reset pulses. With a circulator and another optical band-pass filter we can separate the light of the DFB laser from the injected light and visualize the flip-flop operation on an optical scope. A peltier element and thermistor are used to control the temperature of the DFB laser diode.
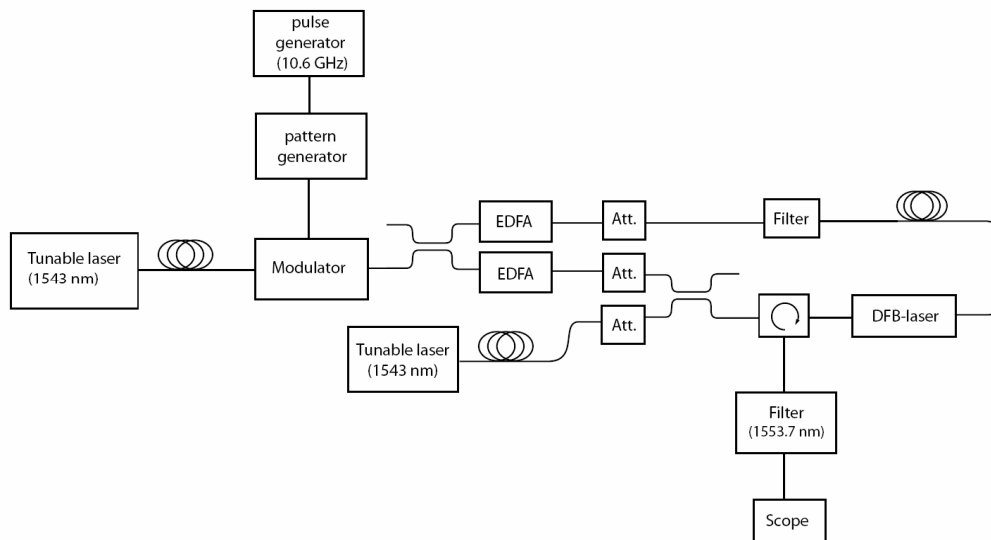

Fig. 4. Schematic of the experimental set-up for flip-flop experiments.

4.2. Experimental result

The resulting flip-flop operation obtained with this set-up is shown in Fig. 5. CW-light with a wavelength of 1543 nm is injected to operate in the bistable regime. Reset-pulses with an energy of 500 fJ and a duration of 100 ps are combined with the CW-light. This causes a depletion of the carriers and thus switch-off the laser. We obtain a switch-off time of 50 ps. The set-pulses which are sent from the other side of the DFB laser, have an energy of only

200 fJ . These switch on the DFB laser by restoring the uniformity within the cavity and a switching time of approximately 100 ps is achieved with an extinction ratio of 15 dB. The repetition rate of the pulses is 1.25 GHz here. The slower switch-on can be explained by the fact that the laser gets slightly into depletion after injection of the set-pulse and the carrier density needs to be built up again.

We found that there is no limitation on the wavelength of the injected light as long as it is outside the stopband of the DFB grating (approximately 3 nm wide). The pulses can also have a different wavelength than the CW-light.
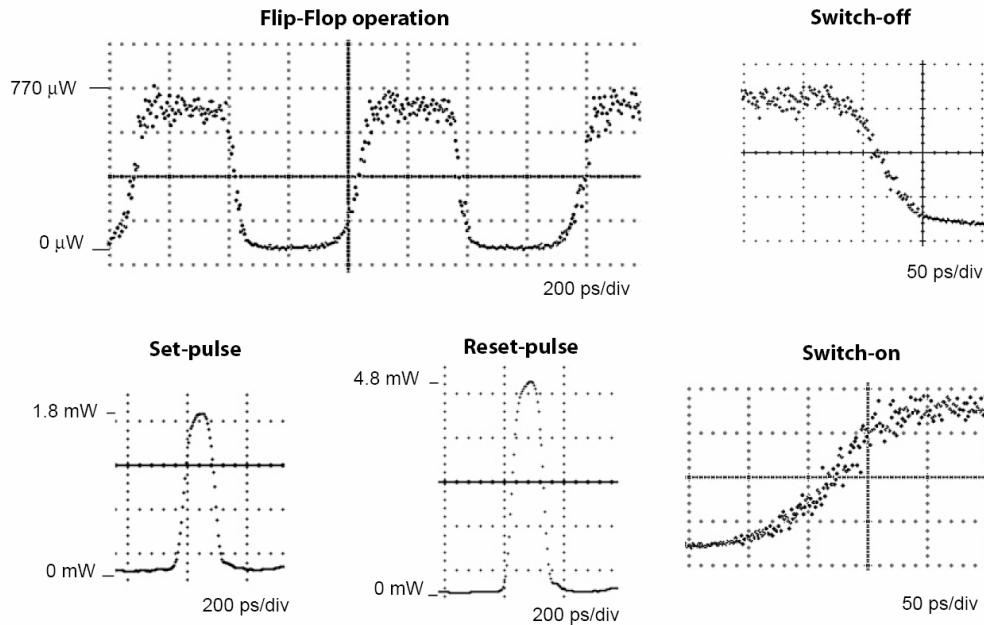
Fig. 5. Experimental results for flip-flop operation using pulses with a length of 100 ps and repetition rates of 1.25 GHz.

4.3. Experimental results with ultra-short pulses

The same experiment is done using an ultra-short pulse source, generating pulses with a duration of only 7 ps. Because the repetition rate of our pico-second pulse source is 10 GHz, we used the modulator to decrease this repetition rate. In our scheme of Fig. 4, the pico-second pulse source replaces the wavelength tunable laser. The bitpattern generator of the modulator and the pulse source are thus driven by the same signal generator. Because the extinction ratio of the modulator is limited to 20 dB, it can not suppress the pulses completely causing less stable results.

The obtained results are depicted in Fig. 6. The set-pulses have an energy of 75 fJ and the reset-pulses 190 fJ. The repetition rate is 1.25 GHz and the switch-on time is now 75 ps. We obtain an almost immediate switch-off of 20 ps which corresponds with the resolution of our optical scope. As illustrated in Fig. 7, we were also able to obtain repetition rates of 2 GHz.
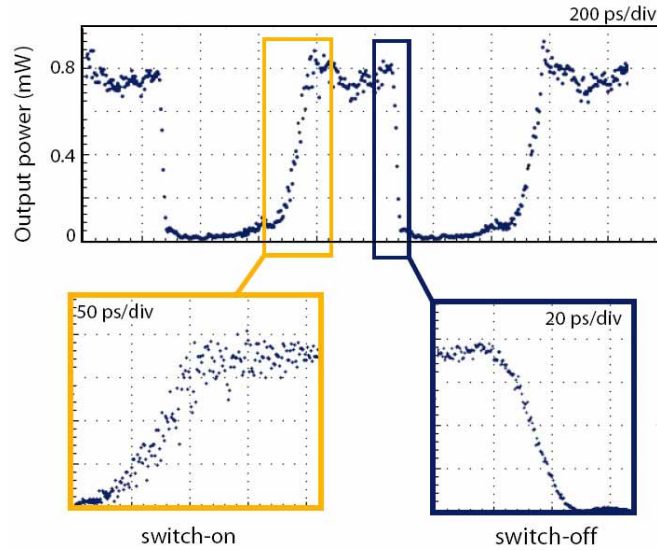
Fig. 6. Experimental results for flip-flop operation using pulses with a length of approximately 7 ps and repetition rates of 1.25 GHz.
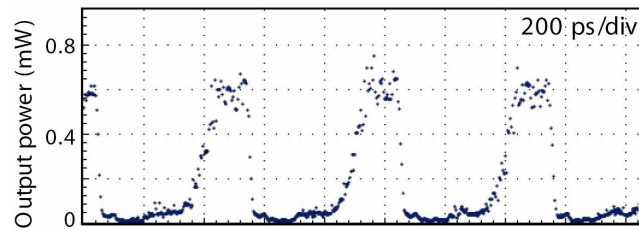

Fig. 7. Experimental result for flip-flop operation using pulses with a length of 7 ps and repetition rates of 2 GHz.

5. Conclusions

We demonstrated experimentally all-optical flip-flop operation in a single Distributed Feedback (DFB) laser diode. Using pulses with repetition rates of 2 GHz and energies below 200 fJ, we obtain switch-on times of 75 ps and almost immediate switch-off of the DFB laser diode. The flip-flop can operate over a broad wavelength range of the injected signals.

Acknowledgments