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All-Optical Flip-Flop Operation in a Standard Tunable DBR Laser Diode

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***Abstract*—A novel concept for all-optical flip-flop operation in a distributed Bragg reflector laser is presented. Using pulses at the same wavelength but with a different duration and amplitude, flip-flop operation is obtained experimentally with switching times of 50 ps and pulse energies of 2–4 pJ.**

***Index Terms*—All-optical flip-flop, bistability, distributed Bragg reflector (DBR) laser.**

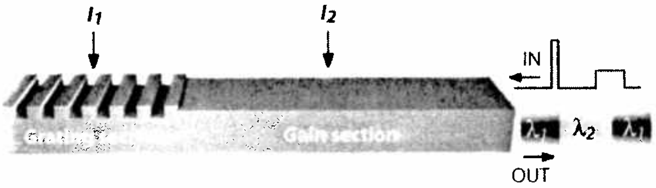

Fig. 1. Concept of switching in DBR laser.

I. Introduction

THE huge growth of upcoming telecommunication services drastically increases the requirements on bandwidth. To overcome the slow and power consuming electrical processing, all-optical packet switching is presented as a feasible solution. Therefore, all-optical flip-flops draw more and more attention as the main building blocks in packet switched networks because of their ability to store the optical header information [1].

In recent years, different concepts for all-optical flip-flops have been proposed, but most of them require the integration of multiple laser sections [2]–[4] or an external holding beam [4]–[6]. Another option is to make use of multimode interference bistable laser diodes [7] but due to the large footprint, these devices have a high power consumption and a rather slow switching time. More recently, flip-flop operation is demonstrated in ring or disk lasers by switching between the clockwise and counterclockwise mode [8]. However, in terms of power consumption and switching times, these disks become only promising when the radius is very small which results in a difficult fabrication and uncontrollable variations on the lasing wavelength.

We demonstrate experimentally all-optical flip-flop operation in a standard tunable distributed Bragg reflector (DBR) laser diode. We use the well-known bistability that is obtained in the tuning characteristics of such a laser [9]. This means that there is no need for an external holding beam and the tunability enables us to control the wavelength easily. Such an all-optical flip-flop has already been proposed in [10], with the switching between the two different wavelengths of the bistability being based on injection locking at those two wavelengths. Here, we demonstrate a novel concept using pulses of the same wavelength but of different duration and amplitude. In [10], no information is given about the achieved switching times. We obtain experimentally flip-flop operation with switching times of 50 ps using set pulses of 10 ps (pulse energy of 2 pJ) and reset pulses of 100 ps (pulse energy of 4 pJ). Because there are many different hops with a bistability, it is straightforward to match the wavelength of the flip-flop with the requirements of the wavelength-division-multiplexed (WDM) system. Moreover, because the pulses are injected at a single wavelength, there is one channel left that has no distortion from the injected pulses.

II. Concept

The all-optical flip-flop that we propose can be either a two- or three-section DBR laser diode, or any other variant of the classical DBR laser diodes. If the laser is long enough and the reflection spectra from the Bragg gratings is broad enough, the laser shows a bistability in the wavelength versus tuning current characteristics at high power levels (gain current above 90 mA in our device). The physical origin is the so-called Bogatov effect [11], an asymmetric gain suppression due to the four-wave mixing between main mode and sidemode.

Flip-flop operation is obtained by using pulses of the same wavelength (corresponding with the highest wavelength branch of the bistability) but with different duration and amplitude (Fig. 1). A long pulse is used to injection-lock the laser at that wavelength. With a very short pulse (10-ps duration in our experiment), we can make the DBR-laser switch back to the lower branch. This lower branch corresponds to a lower carrier density in the gain section. Hence, by depleting the gain section using this short pulse, the laser will automatically relax back to the state with the lowest carrier density and thus the lower branch. This very short pulse can in principle be given at any frequency.

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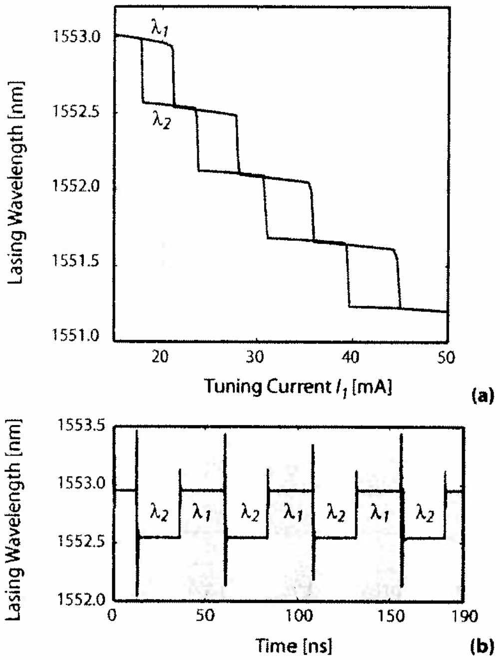


Fig. 2. Simulation results on switching in a DBR laser with active gain section of 600 μm, bias current of 100 mA, grating section length 300 μm, and κ-value 60 cm^{-1}. (a) Multiple bistabilities in the tuning range of the lasing wavelength; (b) time-resolved frequency demonstrating the flip-flop operation.

III. Simulation Results

To illustrate the concept, we simulate it with a commercially available software packet (VPI Transmissionmaker). A standard DBR laser model with a gain section of 600 μm and a bias current of 100 mA is used. By varying the tuning current over a wide range, we obtain the bistabilities as depicted in Fig. 2(a). We use the bistability located at the current of 20 mA and inject pulses with a different duration at a wavelength λ_1. We use pulses with a duration of 100 and 10 ps and corresponding energies of several picojoules (varying from 3 to 6 pJ for set and from 0.5 to 3 pJ for reset). The time-resolved frequency is shown in Fig. 2(b) and flip-flop operation in the frequency domain can be observed. Because the pulses are solely injected at λ_1, we can seperate the signal at wavelength λ_2 with an optical bandpass filter (OBPF) to obtain the flip-flop operation without any distortion coming from the pulses. The rather high value of the tuning current used here (and also in the experiment) is chosen in order to obtain hysteresis over a relatively broad current range and to make the flip-flop less sensitive to current fluctuations, but it is not strictly required.

IV. Experimental Results

We demonstrate the flip-flop operation also experimentally with a standard two-section DBR laser from Alcatel-Thales III/V Labs. The active gain section is a multiquantum-well layer with a length of 600 μm and a current of 100 mA is injected. The Bragg section has a length of 250 μm and a corrugation with $\kappa = 40$ cm^{-1}. The typical tuning range of such devices is 16 nm [9]. Usually, DBR lasers with a shorter active section are used to reduce nonlinear effects and to provide regular tuning control. However, for this application, it is important to have a DBR specially designed to have a strong hysteresis and, therefore, a larger active section. The bistability as a function of the tuning current is depicted in Fig. 3. We see that the laser can operate in a bistable region with a width of 0.5 mA at a wavelength of 1561.3 and 1560.7 nm. The devices under study were not optimized for polarization-independent operation, but such optimization should be theoretically possible.

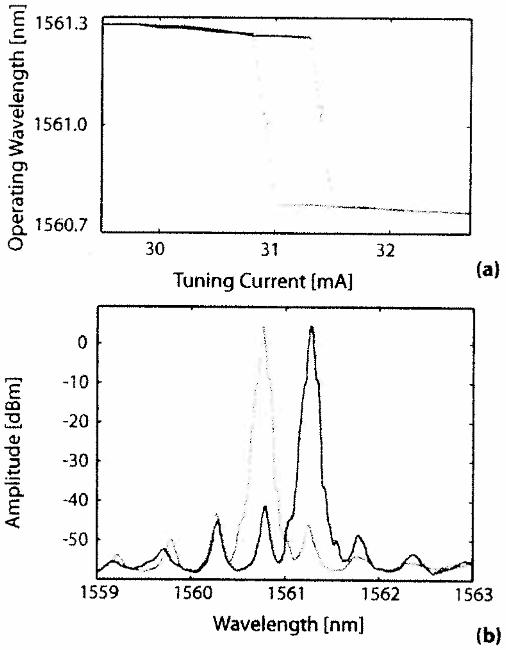


Fig. 3. (a) Bistability in the operating wavelength as a function of the tuning current ($I_{\text{active}} = 100$ mA); (b) optical spectrum of the two states with side-mode supression ratio of 44 dB.

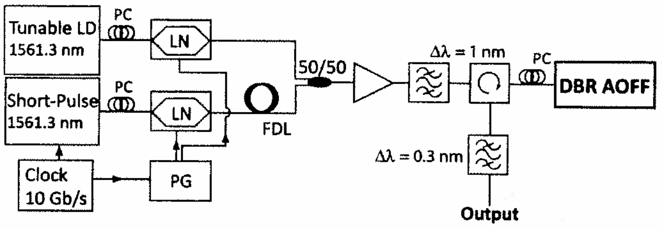
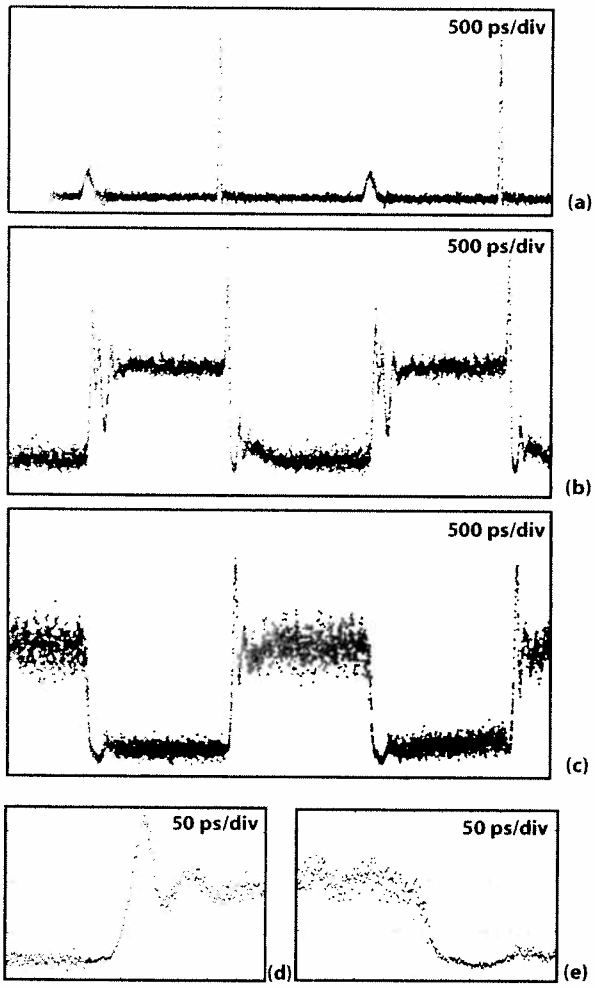


Fig. 4. Schematic of the measurement setup (LD: laser diode; PG: pattern generator; PC: polarization controlling wheels; FDL: fiber delay line; LN: lithium niobate modulator; EDFA: erbium-doped fiber amplifier; AOFF: all-optical flip-flop).

A schematic of the measurement setup is given in Fig. 4. A picosecond pulse source at 1561.3 nm is used to provide pulses of 10 ps with a repetition rate of 10 GHz. By sending these pulses through a modulator, the repetition frequency is decreased. Another modulator is used in combination with a tunable laser to generate the 100-ps pulses and a fiber delay line controls the time difference between the set and reset pulses before combining them. The signals are amplified with an erbium-doped fiber-amplifier (EDFA) and the amplified spontaneous emission (ASE) is removed with an OBPF. Using a circulator, we can separate the output signal from the DBR laser. An OBPF with a very narrow bandwidth (0.3 nm) is used to distinguish the two different output wavelengths.

When we inject pulses at 1561.3 nm, we can obtain flip-flop operation at the other wavelength as depicted in Fig. 5. The long



. 5. Experimental results on all-optical flip-flop operation. (a) Injected es at 1561.3 nm; (b) output at 1561.3 nm; (c) flip-flop operation at 0.7 nm; (d) switch-on; (e) switch-off.

ses of 100 ps act as reset pulses because they injection-lock laser. The short and strong pulses (10 ps) act as set pulses ause they bring the laser in depletion and back to the state h the lower carrier densities (at 1560.7 nm). Switching in less n 50 ps was obtained with set pulses of 2 pJ and reset pulses 4 pJ. Part of this switching time is, however, due to the rise fall times of the 10-Gb/s pattern generator and modulator the reported energies are measured in-fiber (without taking coupling loss of the lensed fiber into account).

V. CONCLUSION

/e demonstrated experimentally a novel concept for flip-flop ation in a single DBR laser. Using pulses with different duration and amplitude but with the same wavelength, we obtain switching times less than 50 ps with pulse energies of a few picojoules. The principle can easily be extended to other tunable laser diodes, e.g., widely tunable laser diodes, that exhibit hysteresis in the tuning characteristics.

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