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1-GHz All-Optical Flip-Flop Operation of Conventional Cylindrical-Shaped Single-Mode VCSELs Under Low Power Optical Injection

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***Abstract*—All-optical set-reset flip-flop operations of conventional circular cylindrical-shaped 1.55-µm wavelength single-mode vertical-cavity surface-emitting lasers (SM VCSELs) have been demonstrated at a switching frequency of 1 GHz based on polarization bistability observed via injection current variation. The energy of set and reset pulses was lower than 4.5 fJ at a bias current of the VCSEL of 4 mA. Polarization bistable VCSELs will be useful for high-speed optical signal processing applications.**

Index Terms— Flip-flops, optical bistability, optical injection, polarization switching, vertical-cavity surface-emitting lasers (VCSELs).

I. Introduction

All-Optical flip-flops (AOFFs) using optical bistable devices can be used for many applications in future high-speed optical networks and optical computing, such as optical switches, optical memories and optical clock generation [1]-[3]. InP-based semiconductor devices such as semiconductor optical amplifiers, distributed feedback laser diodes, Fabry-Perot LDs and micro-disk lasers have been used for demonstration of the AOFF by various research groups[4]-[7]. Low power consumption, high-speed operation and ability for photonic integration of such devices are very important for future practical applications. Recently small and low power flip-flop operation of a hybrid InP integrated micro-disk laser on a silicon-on-insulator (SOI) wafer was reported with low electrical bias current and injected switching pulse energy of 3.5 mA and 1.8 fJ, respectively [7]. However, the hybrid integrated device has a significant coupling loss between the InP device, SOI waveguide, and coupled optical fibers.

VCSELs have been recognized as useful optical devices because of their potential for integration in 2-dimensional arrays, low power consumption, low coupling loss to optical fibers and low cost compared to other devices. Several research reports on the optical bistability of the VCSELs and applications to the AOFF operation have been made previously. However, previous reports are mostly related to observations of optical bistability and AOFF operation with 850-nm or 980-nm wavelength VCSELs [8], [9]. In the optical telecom wavelength region of 1550 nm, AOFF operation based on polarization bistability of a specially designed VCSEL with square-shaped mesa structure was demonstrated, but the optical bistability was observed at a relatively high-operating current of above 14.1 mA [10]. Optical injection induced polarization bistability in commercially available single-mode VCSELs has also been reported, but the injection power required for a hysteresis curve between the two orthogonal polarization states was several hundred microwatt of a continuous-wave mode laser beam [11],[12]. Recently we have observed operating current-induced polarization bistability of conventional cylindrical-shaped single-mode VCSELs at 1.55 µm wavelength, and have also reported a potential for all-optical flip-flop operation with the polarization bistability of the VCSEL [13].

In this letter, we report 1-GHz all-optical flip-flop operation using the polarization bistability of conventional circular cylindrical-shaped 1550-nm wavelength single-mode VCSELs with a low switching energy of 4.5 fJ.

II. Experiments and Results

In this experiment we used commercially available single longitudinal-mode 1.55-µm wavelength VCSELs with circular cylindrical shaped cavity (Raycan). VCSELs with ideal circular symmetry output surface structure can have fundamental transverse mode lasing output in one of two orthogonal linear polarization states, whose directions are aligned with the $\langle 110\rangle$ and $\langle 1\bar{1}0\rangle$ crystal directions of the InAlGaAs/InP compound semiconductor materials. However, due to device asymmetries, birefringence and anisotropy the SM VCSELs deliver a laser output at a well-defined polarization direction for injection currents above threshold current, and show polarization switching and bistability as the injection current varies. The polarization switching and bistability properties of the VCSELs varied from chip to chip even within one wafer, which might depend on amount of anisotropic stresses built up inside each of the VCSEL chips during the fabrication process [13].

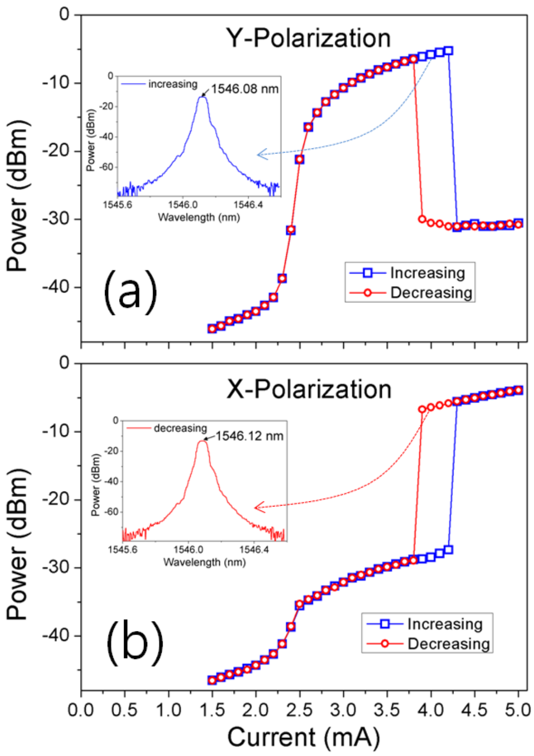

Fig. 1. Measured L-I curves of the bistable VCSEL in (a) Y- and (b) X-polarization directions. Inset: optical spectra of the VCSEL's output at 4 mA with (a) increasing bias current and (b) decreasing bias current.

Fig. 1 shows the polarization switching and bistability conditions in the *L-I* curve of a SM VCSEL versus increasing and decreasing bias current - obtained using the measurement setup shown in Fig. 2. The VCSEL had a threshold current of 2.4 mA at 17.4 ± 0.002 °C. The VCSEL's temperature was controlled with a thermo-electric cooler packaged in its TO-can package. Two different polarization switching currents were observed at a 0.5 mA spacing as shown in Fig.1. The first lasing mode appeared at an initial polarization state, called the Y-polarization mode. As the bias current was increased above 4.3 mA, the output switched abruptly to the orthogonal polarization state, called the X-polarization mode. On the other hand, as the bias current was decreased from a high current, the X-polarization mode output switched back to the Y-polarization mode output at 3.8 mA. The insets of Figs. 1 (a) and (b) represent optical spectra measured with an optical spectrum analyzer (OSA) at a bias current of 4.0 mA as the current was increased and decreased, respectively. The corresponding VCSEL output powers were -9.6 dBm in the Y-polarization and -10.0 dBm in the X-polarization for increasing and decreasing current respectively. The wavelength separation of the spectral peaks between the two orthogonal polarization states was about 0.04 nm.

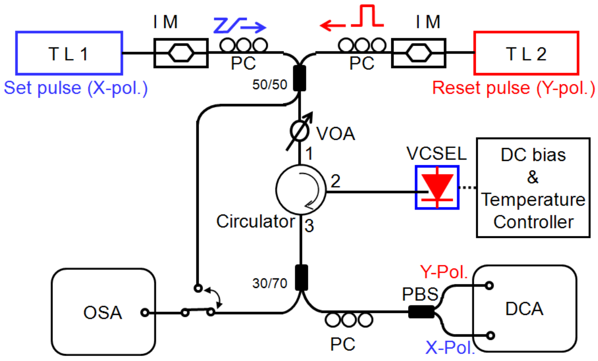

Fig. 2. Experimental setup for all-optical flip-flop operation with injection of set and reset pulses.

Polarization bistability based AOFF operations were performed with the experimental setup shown in Fig. 2. Modulated signal pulses from two tunable lasers (TLs) with Mach-Zehnder intensity modulators (IMs) were used for the set and reset optical pulses. The intensity modulators (IMs) were driven with a 3.2 GHz pulse pattern generator. The set and reset pulses were passed through a 50/50 directional coupler, a variable optical attenuator (VOA) and an optical circulator, and then injected into the VCSEL. The output from the VCSEL passed through the same optical circulator, a 30/70 directional coupler, another polarization controller, and a fiber-type polarization beam splitter (PBS). Two separated orthogonal polarization output from the PBS were measured with a digital communication analyzer (DCA) with two 20 GHz photoreceiver modules.

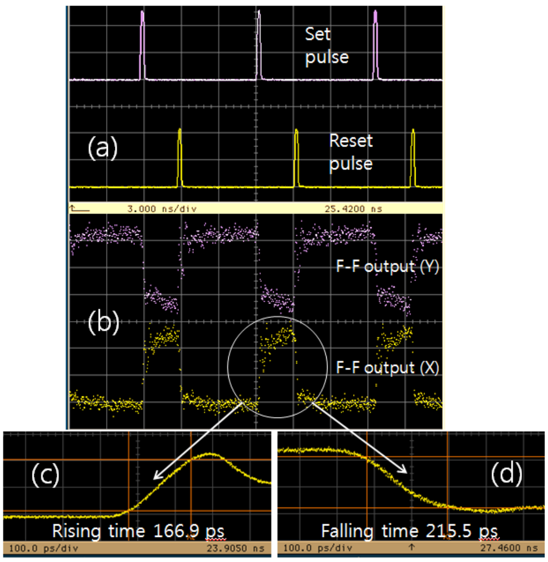

Fig. 3. Waveforms of the (a) set /reset pulses and (b) flip-flop output at a 346 MHz switching frequency. (c) and (d) show the rise and fall times of the switch-on and switch-off transients, respectively.

We first performed a low repetition rate AOFF operation to test the switching time. The VCSEL was operated at a driving current of 4.0 mA which was within the bistable region. Initially the VCSEL's output was adjusted to deliver a Y-polarized output at 1546.08 nm. The wavelengths of TL 1 (set) and 2 (reset) were adjusted to about 1546.12 and 1546.08 nm, respectively, which corresponded to the peak wavelengths of the X- and Y-polarization outputs as shown in Fig. 1. Fig. 3 (a) shows the measured pulse patterns of injected set and reset pulses, each of which had a pulse width of 280 ps and a rising time of 112 ps. When a set pulse stream in the X-polarization direction was injected into the VCSEL, the output was switched from the Y-polarization state to the X-polarization state at a wavelength of 1546.12 nm, and then was kept in the switched X-polarization state. For injection of the reset pulses in the Y-polarization direction the X-polarization output was returned back to the Y-polarization as shown in Fig. 3(b). Figs. 3 (c) and (d) show the switch-on and switch-off times of the AOFF signals, each of which are 166.9 ps and 215.5 ps, respectively. These temporal response times might be reduced further by using injection pulses of short pulse width as shown in Ref. 5. Based on the measured switch-on and switch-off times the VCSEL can be used for AOFF operation at frequencies greater than 2 GHz.

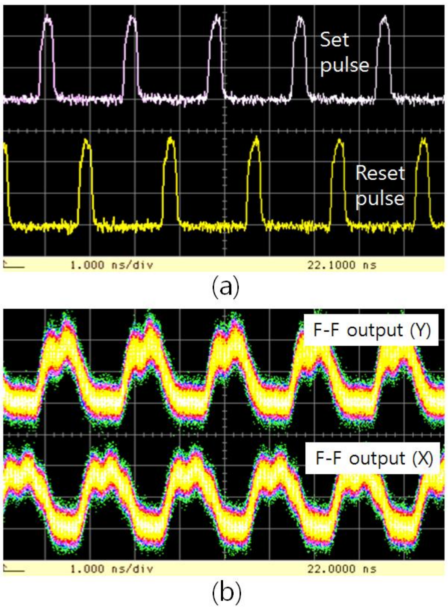

Fig. 4. All-optical flip-flop operation for 1 GHz switching frequency: (a) the set and reset signals injected into the VCSEL and (b) oscilloscope traces of the flip-flop outputs accumulated for an acquisition time of 20 sec.

Fig. 4 shows the measured waveforms of the AOFF operation of the SM VCSEL at a switching frequency of about 1 GHz. The injected pulse energies of the set and reset pulses into the VCSEL were only 4.5 fJ and 3.5 fJ, respectively. These values of the injection pulse energies for the flip-flop operation are less than those reported in Ref. 10 where a VCSEL of square-shaped mesa structure was used instead of the conventional circular cylindrical-shaped VCSELs. The operation speed can be further enhanced if very short injection pulses are used.

III. CONCLUSION

We have demonstrated 1 GHz AOFF operation of a conventional circular cylindrical-shaped 1.55-µm wavelength SM VCSEL under low power optical injection based on its polarization bistability. The pulse energy of set/reset signals was smaller than 4.5 fJ, and the bias current of the VCSEL was 4 mA. Further improvement of switching speed of the flop-flop operation can be achieved with high speed pulse generators. AOFF operation based on polarization bistable VCSELs will be useful for cost-effective applications in high-speed signal processing in future optical switching, optical router, optical memory, and optical computing.

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