Semiconductor active devices for all-optical signal processing

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ABSTRACT

After a brief introduction of optical bistable operation of semiconductor active devices such as LDs and SOAs, recent progress in polarization bistable VCSELs and their applications for all-optical signal processing are presented. Applications include all-optical flip-flop operation with very low switching energy and high repetition rate, all-optical signal regeneration, and optical buffer memory.

Keywords: bistability, polarization, VCSEL, all-optical signal processing, regeneration, optical buffer memory

1. INTRODUCTION

Bistable laser diodes (BLDs) are expected to be key components in the future optical communication and switching systems[1]. The research of bistable laser diodes began by the Lasher's proposal of a two section laser diode in 1964[2]. We predicted that there are two kinds of polarization bistability, i.e., S-shaped bistability and pitchfork bifurcation bistability through gain saturation of laser diodes[3]. The later one has a major speed advantage over the former one. We experimentally observed the pitchfork bifurcation bistability in a vertical-cavity surface-emitting laser (VCSEL)[4] and reported a gigahertz all-optical flip-flop operation using the polarization bistability[5]. Ultrafast polarization bistable switching with a 7 ps switching-time in a VCSEL was also successfully demonstrated[6,7].

In this paper, recent progress in polarization bistable VCSELs and their applications for all-optical signal processing are overviewed together with a brief introduction of optical bistable operation of semiconductor active devices such as LDs and semiconductor optical amplifiers (SOAs). Polarization bistable switching has been successfully demonstrated in the VCSELs with a square mesa-structure, which is simply made by reactive ion etching (RIE) technique. We experimentally demonstrate all-optical flip-flop operation with very low switching energy and high repetition rate and signal regeneration using a polarization bistable VCSEL. Optical buffering for photonic packet switching is also proposed.

2. OPTICAL BISTABLE LASER DIODES AND SOAS[8]

2.1 Optical bistability

Optical bistability, as the term implies, refers to the situation in which two stable optical output states are associated with a single optical input state. Two general requirements must be satisfied for optical bistability to occur. The first is that there must exist an appropriate system parameter, such as the absorption or gain coefficient or refractive index, which depends on optical input intensity. The second is the existence of a feedback mechanism. Hysteresis occurs both in a counterclockwise sense and in a clockwise sense. These types of hysteresis are called S-shape bistability.

Pitchfork bifurcation is usually defined as a form represented by the following differential equation, which depends on a single parameter μ:

$$\frac{dx}{dt} = \mu x - x^3 \quad (1)$$

Here, the only bifurcation point is $(\mu, x) = (0, 0)$. The unique fixed point $x = 0$ existing for $\mu \leq 0$ is stable, and it

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becomes unstable for $\mu > 0$. The new bifurcating fixed points at $x = \pm\sqrt{\mu}$ are stable. Many types of bistability that have shapes similar to pitchfork bifurcation appear in two-mode LDs. These are called pitchfork bifurcation bistability.

2.2 Absorptive bistability

LDs that include saturable absorbers in their cavity show bistability in the optical-output-versus-current curve and in the optical-output-versus-optical-input curve. In the OFF state of a BLD, there will be no laser action. In the ON state, the device operates as a laser. The population in the absorber is inverted by optical pumping from the gain region so that it is essentially transparent to the laser radiation. The quasi-Fermi level in the gain region decreases as it goes from OFF state to ON state, while, in the absorber, it increases. The two states of the device are stable.

One example of absorptive BLDs is the InGaAsP DFB BLD structure in which the p-type electrode was divided into three parts, and the divided regions can be excited independently through the electrodes[9]. If the current of one region is set at zero or a low value, this region acts as a saturable absorber. It is then possible to obtain bistable characteristics. The minimum input coupled switch-on energy of 0.7 fJ was reported for a bistable three-section laser[10]. Characteristics of voltage-controlled MQW BLD's was simulated, and a turn-off less than 10 ps and a repetition rate of over 5 GHz were expected from the calculations[11]. The side-injection-light-controlled bistable laser diode (SILC-BLD) which consists of a main waveguide laser for output and an orthogonally crossed subwaveguide gate for input was demonstrated. For decreasing parasitic capacitance of the laser, a SILC-BLD buried with semi-insulating InP was developed. 2.5 Gbit/s demultiplexed output signals are each selected once every 4 bits from 10 Gbit/s NRZ optical input signals using this SILC-BLD[12].

One important problem is that of improving the switching spend and repetition rate. Progress are indicated in Fig. 1 together with other types of bistable devices described later.

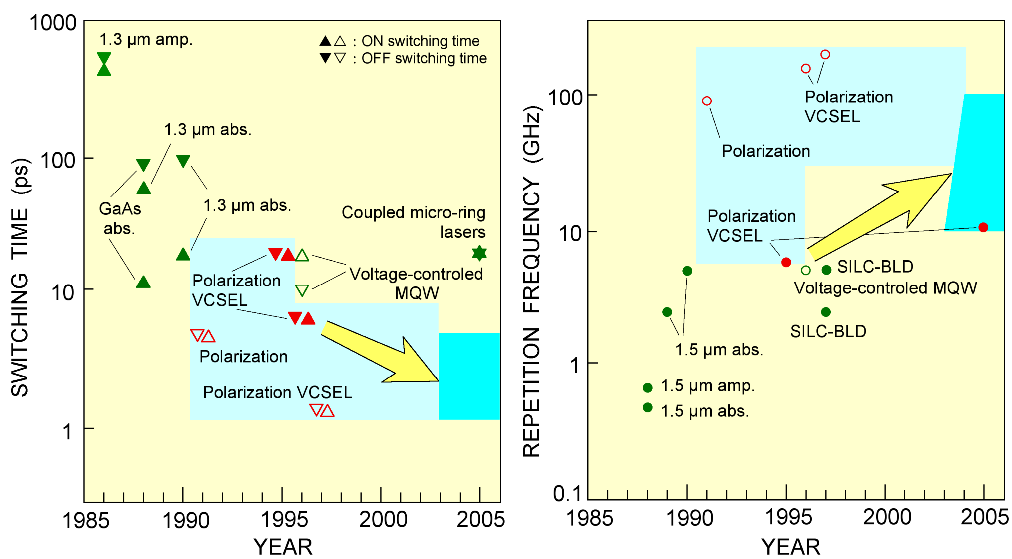


Fig. 1. Progress in performances of bistable laser diodes.
(▼, ▲, and ● are experimental values and ▽, △, and ○ are theoretical ones.)

2.3 Dispersive bistability

A resonant-type LD amplifier, consisting of a normal LD biased below the laser oscillation threshold, can act as a nonlinear cavity and shows bistability in the optical input-output characteristics. This is because the active layer refractive index changes due to gain saturation by light injection. In the reflected light, a rich variety of behavior is observed[13]. The operation of an optical switch requiring 0.5 fJ of incident optical energy was reported for a resonant-type LD amplifier[14].

2.4 Two-mode bistability via gain saturation

If a laser is oscillating in two different modes, the cross-effect between the two modes arises via gain saturation . The rate of change of one-mode intensity also depends on the intensity of the other:

$$\frac{dI_1}{dt} = g_1(1 - \varepsilon_{11} I_1 - \varepsilon_{12} I_2) I_1 \tag{2}$$

$$\frac{dI_2}{dt} = g_2(1 - \varepsilon_{21} I_1 - \varepsilon_{22} I_2) I_2 \tag{3}$$

, where ε_{11} and ε_{22} are self-saturation and ε_{12} and ε_{21} are cross-saturation coefficients. Two possible characteristic situations, weak coupling and strong coupling, can occur. If $\varepsilon_{11}\varepsilon_{22} > \varepsilon_{12}\varepsilon_{21}$ (weak coupling), in general, there can be stable one- or two-mode operation. Bistability will occur if $\varepsilon_{21}\varepsilon_{12} > \varepsilon_{11}\varepsilon_{22}$ (strong coupling). In this strong-coupling case, only one of the modes oscillates, the other mode being suppressed. In the resulting steady state, therefore, the laser does not oscillate simultaneously in two modes, but it oscillates in only one of the modes.

We calculated self- and cross-saturation coefficients by solving the equation of motion for the density matrix perturbationally, where the optical field was described by Maxwell equations, while the electronic structure was calculated quantum mechanically by diagonalizing the Luttinger's Hamiltonian[15]. The numerical calculations for active lasers of bulk InGaAsP[15], InP/InGaAsP MQW[16], and strained MQW[17] show that the condition $\varepsilon_{21}\varepsilon_{12} > \varepsilon_{11}\varepsilon_{22}$ for polarization bistability is satisfied for all cases.

Polarization bistability between the transverse electric (TE) and transverse magnetic (TM) mode was observed in an external cavity LD[18]. The pitchfork bifurcation bistability was experimentally observed in a VCSEL and 1.2 GHz all-optical flip-flop operation using polarization bistability was successfully demonstrated[4]. Very recently, bistable switching between two lasing modes of micro-ring lasers has been reported; laser light traveling in the clockwise direction, and laser light in the anticlockwise direction[19]. The device switches within 20 ps with 5.5 fJ optical switching power.

3. POLARIZATION BISTABILITY

3.1 Polarization bistable switching

The polarization bistable operation in a VCSEL is schematically shown in Fig. 2. A VCSEL that has a 6 x 6 μm square mesa-structure was used in our former experiments[20]. The VCSEL showed a polarization switching between 0° polarization and 90° polarization[4]. The bistable switching between the two orthogonal polarizations was obtained by optical injection pulses with two orthogonal polarizations. The VCSEL initially oscillated with 90° polarization. When a 0° polarization trigger pulse was injected, the VCSEL switched its polarization from 90° to 0°, and remained at 0° polarization. In the 0° polarization state, when a 90° polarization trigger pulse was injected, the polarization of the

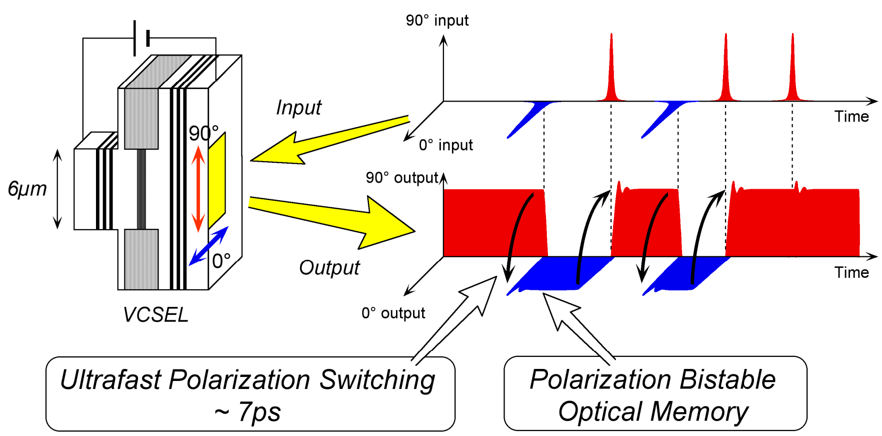
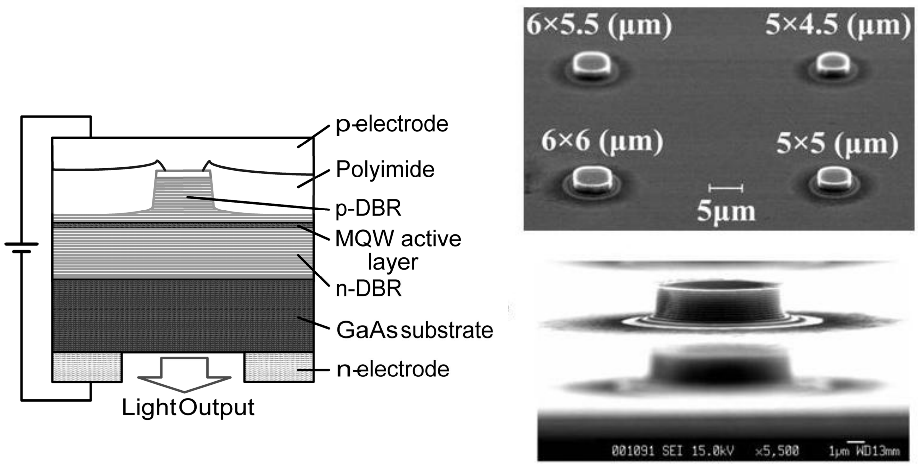


Fig. 2. Schematic illustration of the polarization bistable operation in a VCSEL.

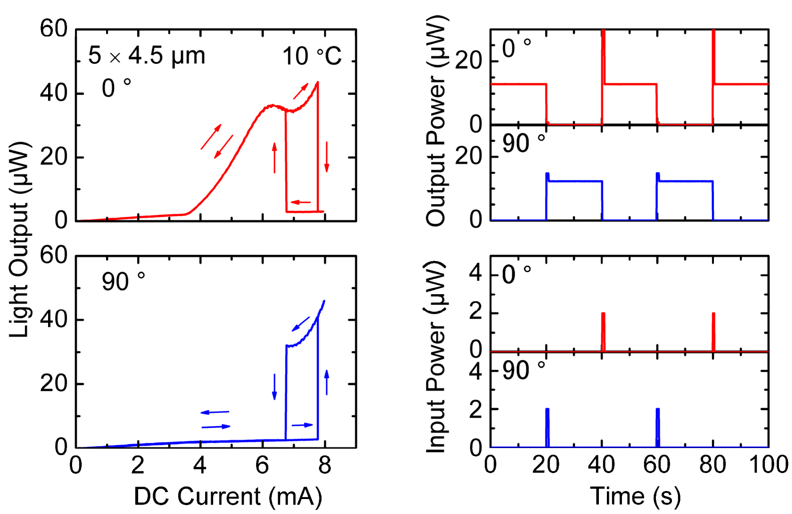
VCSEL changed from 0° to 90°. If the optical trigger input having the same polarization as the VCSEL is injected, the polarization state of the VCSEL does not change. Stable bistable switching operation with low injection light power has been realized, when the wavelengths of the injection lights have been independently optimized. This is because the lasing wavelengths of two polarization states are slightly different (a few GHz) [21].

We have recently prepared a VCSEL with a square mesa-structure using our own facilities (Fig. 3(a)) [22,23]. The square mesa-structure was simply made by RIE (Fig. 3(b)) and embedded in a spin-coated polyimide layer. The small size of the device ensured its stable single transverse mode operation. The measured polarization resolved light output versus current (L-I) curves for the 5 x 4.5 μm mesa-structure VCSEL (Fig. 4(a)) show clear hysteresis. The bistable switching between the orthogonal polarizations was obtained by injection of optical pulses with two orthogonal polarizations (Fig. 4(b)). The bias current was 6.4 mA and the device temperature was 15 °C. This result clearly indicates that the polarization bistability is a very basic characteristic of VCSELs having a square shaped waveguide rather than a peculiar characteristic obtained from a special VCSEL structure and a device process.



(a) (b)

Fig. 3. Structure of the polarization bistable VCSEL. (a) schematic structure. (b) SEM photograph of the mesa-structure.



(a) (b)

Fig. 4. Experimental results of polarization resolved L-I curves (a) and all-optical flip-flop operation (b).

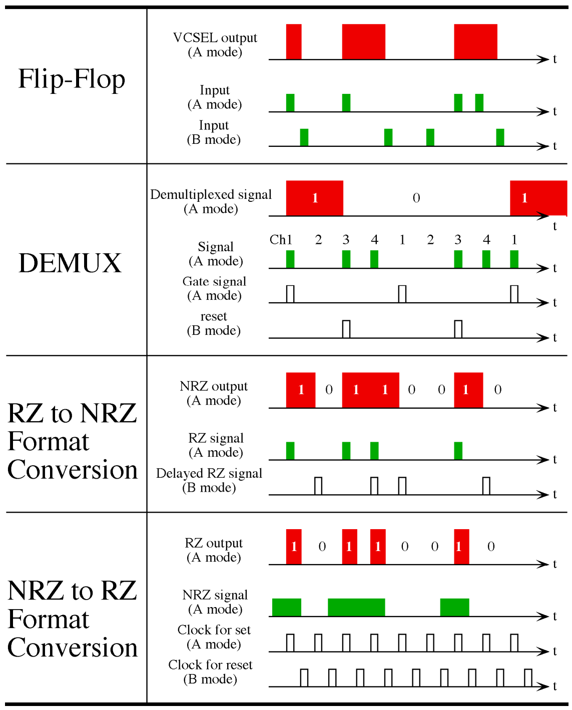
3.2 All-optical signal processing

We experimentally demonstrated many kinds of all-optical signal processing as shown in Table 1, using the memory function and thresholding function of the polarization bistable VCSEL.

3.2.1 Flip-flop operation

Optical flip-flop operation with low injection power has been realized by the optimization of the injection light

Table 1. All-optical signal processing using a polarization bistable VCSEL.



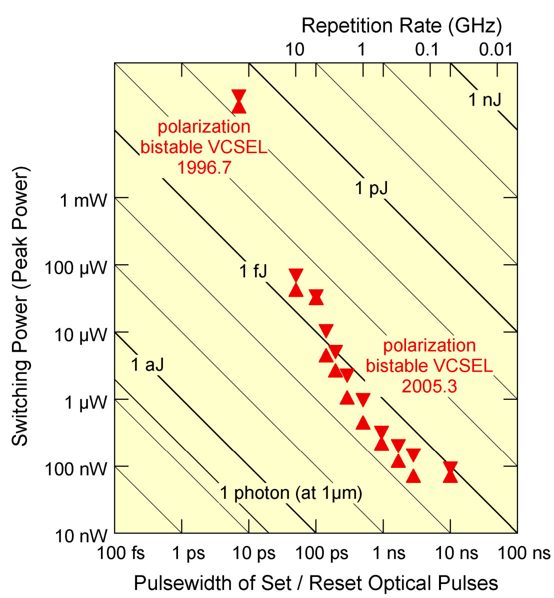


Fig. 5. Switching power vs. set / reset pulsewidth for polarization bistable VCSELs.

wavelengths[24]. The pulse energies of the set and the reset pulse were 0.2 fJ and 0.3 fJ, respectively. The switching frequency was 540 MHz, and the injection pulse width was 0.9 ns. The all-optical flip-flop operation at a repetition rate of 10 GHz has also been successfully demonstrated[25]. The injection pulse width was 50 ps. The pulse energies of the set and reset pulse were 2.0 fJ and 3.5 fJ, respectively. To the best of our knowledge, these results are the lowest switching energy and the highest switching frequency for all-optical flip-flop operation of bistable lasers, respectively.

Figure 5 is the relationship between the injection pulse width and required injection power for the all-optical flip-flop operation. An increase of the injection power in cases where the pulse width is less than 1 ns was steeper than the constant energy line. We reported the ultrafast flip-flop operation of 7 ps switching time using short injection pulses of 1 ps width at 80 MHz repetition rate[6] and this result is also shown in Fig. 5. The pulse energies of the set and reset pulse for the ultrafast flip-flop operation were 160 fJ and 220 fJ, respectively.

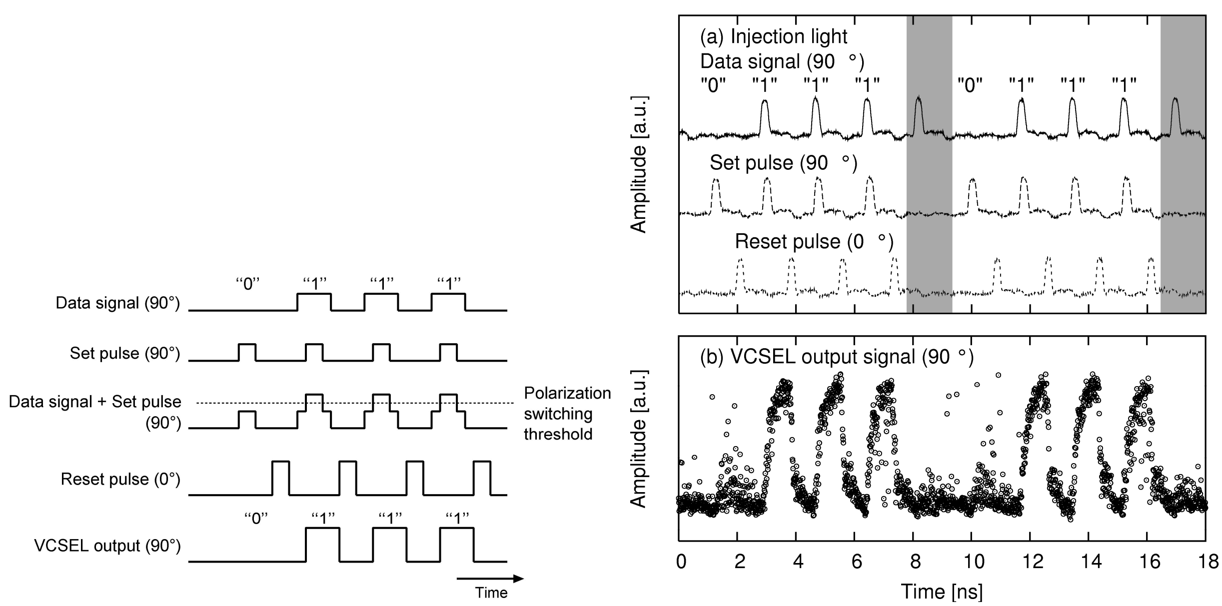
3.2.2 Demultiplexing and format conversion

We experimentally demonstrated both all-optical demultiplexing with a signal-bit width conversion function from high bit rate multiplexed signals[26] and the all-optical format conversion both from RZ to NRZ and from NRZ to RZ[27,28]. Format conversion between different transmission schemes, such as between RZ format and NRZ format, may become an important operation for future optical networks. For many systems, particularly those in which dispersion plays a consequential role, the NRZ transmission format may be preferable.

3.2.3 Signal regeneration

Principle of the all-optical regeneration using a polarization bistable VCSEL is shown in Fig. 6 (a). Each injection power of a data signal and a set pulse are set to less than the polarization switching threshold of the VCSEL. When both of the data signal and the set pulse are injected simultaneously, the injection power exceeds the polarization switching threshold and lasing polarization of the VCSEL is switched from 0° to 90°. Then, the polarization of the VCSEL stays at 90°. When a reset pulse is injected, lasing polarization of the VCSEL returns to 0°. Thus, the VCSEL output signal through a polarizer of 90° becomes the regenerated signal of the data signal.

The experimental results of the all-optical regeneration using polarization bistability are shown in Fig. 6 (b). The data signal to be regenerated had a bit pattern of "0111 0111". Due to the limitation of the pattern generation, the injection lights in hatching area of Fig. 6 (b) are invalid as regeneration of the data signal. The greater part of sampling points in the sampling oscilloscope trace of the VCSEL output signal showed proper regeneration of the data signal. The average data signal power was 0.08 µW, the average set pulse power was 0.10 µW and the average reset pulse



(a) (b)

Fig. 6. Principle (a) and experimental results (b) of the all-optical regeneration using polarization bistability.

power was 0.6 μW. The data signal and the set pulse had the same wavelength, and were mixed in the same phase. Wavelengths of the data signal and the reset pulses were independently optimized. The average output power was 140 μW. Thus the all-optical regeneration has large optical gain.

3.2.4 Optical buffer memory

Optical buffer memory is one of the key devices for realization of photonic packet switching. We propose the optical buffer memory using a two-dimensional array of the polarization bistable VCSELs. A schematic diagram of the proposed optical buffering is shown in Fig. 7. First, the polarizations of the polarization bistable VCSELs of the first column are reset to 90° by an optical reset pulse with 90° polarization. Ultrafast optical signals are converted to spatially parallel signals by a time-to-space converter, and injected into the VCSELs together with optical set pulses. Only when the optical signals and the optical set pulses are simultaneously injected into the VCSELs, the VCSELs change their polarization from 90° to 0°. Therefore, the VCSELs emit the outputs with the polarizations which depend on '0' and '1' of the input signal. Then the optical gates between the first and the second column are opened and the data memorized in the first column are transferred to the second column and are memorized. Only the 0° output from the VCSELs of the last column transmits through an analyzer. The output signal pulses are created from the CW output of the VCSELs using optical gates and are converted to an ultrafast optical signal by a space-to-time converter. Thus optical buffer memories with a shift register function are realized. We have achieved a 1-bit storage and read-out of optical signal and are now doing experiments to demonstrate the optical buffering.

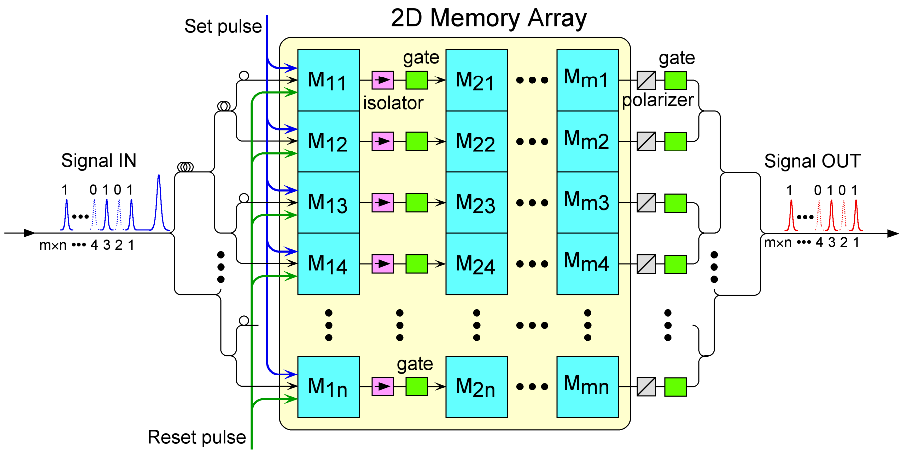


Fig. 7. Schematic diagram of the proposed optical buffering.

4. CONCLUTION

Recent progress in all-optical signal processing using a polarization bistable VCSEL has been reported. These devices may become important devices for all-optical regeneration and optical buffering in the future optical communication.

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