# Optical Multistability Using Optoelectronic Feedback

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*Abstract*—**An optical multistable device with good tuning capability is experimentally realized by using a semiconductor light-emitting device, a photodiode, and transistors with positive optoelectronic feedback. In this device, the number of stable states is determined by the number of transistor pairs. A graphical solution method, as well as a stability analysis of solutions, is presented to explain the operational principle of this device.**

## I. Introduction

INTRINSIC and hybrid optical bistability have been demonstrated in various configurations [1]. However, only a small number of experimental results have been reported for optical multistability [1]–[3]. The hybrid optical devices based on optoelectronic feedback are operated at low optical power with a very wide range of wavelengths and with any polarizations. With these attractive features, various optical logics [3]–[6], flip-flops [3]–[7], and multistability [2], [3] have been studied experimentally. Especially, the multivalued logic based on multistability is important to reduce complexity of devices and interconnections since it increases the information capacity of each line and each storage element as compared to the binary logic.

Recently, optical bistability and optical multistability using positive optoelectronic feedback were presented [8]. In this paper, we report optical multistability using a laser diode, a photodiode, and transistors with positive optoelectronic feedback. By tuning a parameter, we realize optical multiple multistable and multiple bistable loops. This device also gives an electrical output signal. The multistable device requires only a laser diode and a photodiode regardless of the number of stable states. A pair of transistors determines a stable state. This device is simple to integrate and may be used in optical digital computers. A method of graphical solution is presented as well as a stability analysis of the solutions for the laser system with optoelectronic feedback. Using these methods, we obtain bistable and multistable solutions.

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## II. Optical Bistability

First consider optical bistability as the simplest form of optical multistability. The optical bistable device consists of a laser diode, a photodiode, and an amplifier. The block diagram and the circuit diagram of the bistable device are shown in Fig. 1. The optical output of the laser diode (LD) is fed to the photodiode to form a positive feedback loop. The positive optoelectronic feedback and the nonlinearity of the transistor bring about the optical bistable characteristics. The optical output of an ideal laser diode $P_o$ is given by

$$P_o = \begin{cases} k(I_f + I_b - I_{\text{th}}) & \text{for } I_f + I_b \geq I_{\text{th}} \\ 0 & \text{for } I_f + I_b \leq I_{\text{th}} \end{cases} \quad (1)$$

where $I_f$, $I_b$, and $I_{\text{th}}$ are the feedback current, the bias current of the laser diode, and the threshold current of the laser diode, respectively. The constant $k$ represents the conversion efficiency of the laser diode from the injection current to the light output. Typically, the threshold current is $\sim 10$ mA and the conversion efficiency is $\sim 1$ mW/mA for GaAs laser diodes. The characteristics of the amplifier plus the photodiode have cutoff and saturation. Its transfer function may be assumed as piecewise linear. The piecewise linear characteristics can be realized easily by using an ordinary electronic active element such as the transistor and the field effect transistor. Then, the feedback current $I_f$ is given by

$$I_f = \begin{cases} 0 & \text{for } c_2 P_i + c_1 P_o \leq I_c \\ I_s & \text{for } c_2 P_i + c_1 P_o \geq I_c + I_s/A \\ A(c_2 P_i + c_1 P_o - I_c) & \text{otherwise} \end{cases} \quad (2)$$

where $P_i$ is the optical input power, $I_c$ is the cutoff current of the amplifier input, and $I_s$ is the saturation current of the amplifier. The constant $c_1$ represents the coupling efficiency of the optical output of the laser diode to the photodiode; the constant $c_2$ represents the coupling efficiency of the optical input power to the photodiode. They include the conversion efficiency of the photodiode from optical power to current, i.e., $c_2 P_i + c_1 P_o$ is the input current of the amplifier. The constant $A$ is the linear gain of the amplifier.

For the circuit diagram shown in Fig. 1(b), the cutoff current, the saturation current, and the gain of the ampli-

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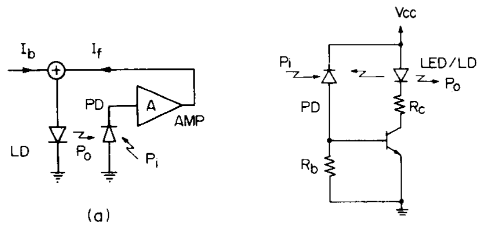



(a) (b)

Fig. 1. (a) Schematic diagram of the optical bistable device. (b) Circuit diagram of the optical bistable device.

fier are given by [9]

$$I_c = V_\gamma / R_b$$

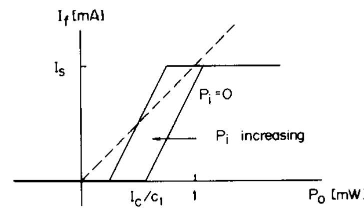
$$I_s = (V_{cc} - V_{ld} - V_{cesat})/R_c$$

$$A = h_{FE}/[1 + k_B T/(qR_b I_{bt})] \quad (3)$$

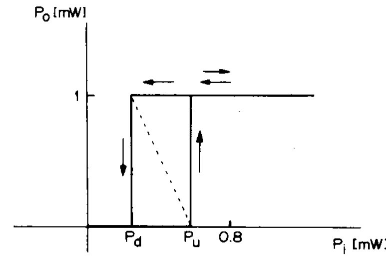
where $V_\gamma$ and $V_{cesat}$ are the cut-in voltage and the collector-to-emitter saturation voltage of the transistor, respectively. $R_b$ and $R_c$ are the resistance of resistors connected to the base and the collector of the transistor, respectively. $V_{cc}$ is the supplied voltage and $V_{ld}$ is the voltage drop across the laser diode. $I_c$ is inversely proportional to the collector resistance $R_b$. $h_{FE}$ is the dc current gain of the transistor and it may be regarded as constant over the operation range of the transistor. $k_B$ is the Boltzmann constant, $T$ is the absolute temperature, $q$ is the charge of electron, and $I_{bt}$ is the base current of the transistor. The gain decreases as $R_b$ decreases. For silicon transistors, the typical value of $V_\gamma$, $V_{cesat}$, and $h_{FE}$ are $\sim 0.6$ V, $\sim 0.2$ V, and $\sim 50$, respectively. Thus, $I_c$ is about 0.1 mA with $R_b = 6$ kΩ. $V_{ld}$ is about 2 V for GaAs laser diodes. The optical output versus the optical input characteristics of our device may be deduced from (1) and (2).

The solutions of (1) and (2) are obtained graphically and shown in Fig. 2(a). To get a graphical solution, we plot the $I_f$ versus $P_o$ curve first by using (1) with $I_b$ chosen for simplicity to be the same as the threshold current and next by using (2) with $P_i$ as a parameter. The solutions are the points of intersection. Fig. 2(a) shows graphical solutions of equations with parameters chosen to get optical bistability. The straight dashed line represents $I_f$ versus $P_o$ for the laser diode with fixed bias current at a lasing threshold, and two $S$-shaped piecewise linear curves represent $I_f$ versus $P_o$ for the feedback network for two different values of $P_i$. At zero optical input power, the optical output power is zero. The piecewise linear curve moves to the left as the optical input power increases and there are three optical output powers for a given optical input. As we further increase the optical input power, the optical output becomes again a single-valued function of the optical input. Fig. 2(b) shows optical bistability corresponding to Fig. 2(a) since the negative slope portion is unstable.

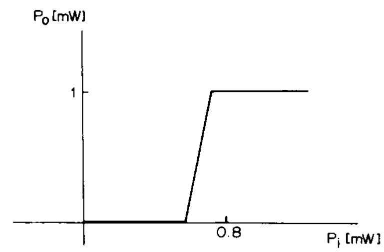
Among steady-state solutions, the stable solutions are easily observed in experiment. The stability of steady-state solutions may be checked by the dynamical model



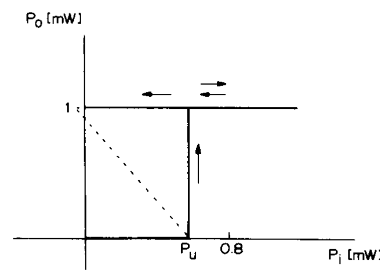

(a)




(b)




(c)




(d)

Fig. 2. (a) Graphical solutions of the optical bistable device with $c_1 = 0.5$, $k = 1$ mW/mA, $I_s = 1$ mA, $I_c = 0.28$ mA, and $A = 2.94$. (b) Optical bistability, (c) optical amplification, and (d) optical thyristor characteristics.

of the device. However, there exists a simple method for stability analysis of the optical bistable and multistable devices. The stability of steady-state solutions may be checked by the slopes of two curves appearing in the graphical solution method, i.e., estimation of the closed-loop gain. The steady-state solutions are unstable when the steady-state solution satisfies the following condition:

$$\left(\frac{dP_o}{dI_f}\right)_{ld} \left(\frac{dI_f}{dP_o}\right)_{fn} > 1 \quad (4)$$

where the subscripts *ld* and *fn* represent the laser diode and the feedback network, respectively. This is the condition of the regenerative amplification of small perturbations from the steady state (i.e., the closed-loop gain of the feedback loop must be greater than one). Here, we have used this condition in checking the stability of the steady-state solutions of bistable and multistable devices.

To get optical bistability, the closed-loop gain of the feedback loop $c_1kA$ must satisfy the following condition:

$$1 < c_1Ak < (I_s + AI_c)/(I_b + I_s - I_{\text{th}}). \tag{5}$$

Physically, the lower limit comes from the condition for regenerative amplification of the feedback optical power. In other words, the closed-loop gain of the feedback loop must be greater than one. Since the typical values of $c_1$ and $k$ are $\sim 0.4$ mA/mW and $\sim 1$ mW/mA, respectively, the minimum required gain of the amplifier for bistable operation is $\sim 2.5$. It is easy to realize this amplifier by using an ordinary transistor. If the closed-loop gain is less than one, the device shows well-known optical transistor characteristics, as shown in Fig. 2(c). The gain of the optical transistor is inversely proportional to $1 - c_1Ak$ and larger optical gain requires narrower bandwidth. The upper limit in (5) is the condition for existence of the "ON" to "OFF" transition at nonzero optical input power. If the closed-loop gain is greater than the upper limit, the optical input/output characteristics of the device are similar to that of a thyristor in electronics. The optical output versus the optical input of this device is shown in Fig. 2(d).

A condition is imposed on the the cutoff characteristics of the amplifier or the threshold of the laser diode. This arises from the condition for the existence of an "OFF" to "ON" transition at nonzero optical input power. The optical input power at the "OFF" to "ON" transition point $P_u$ is given by

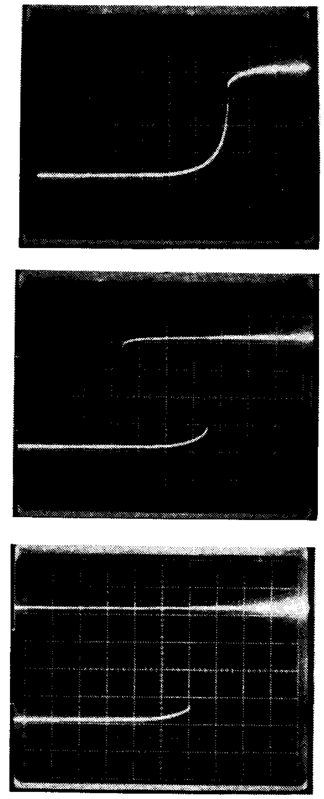
$$c_2P_u = \begin{cases} I_c - c_1k(I_b - I_{\text{th}}) & \text{for } I_b \geq I_{\text{th}} \\ I_c + (I_{\text{th}} - I_b)/A & \text{for } I_b \leq I_{\text{th}}. \end{cases} \tag{6}$$

To get the "OFF" to "ON" transition at nonzero optical input power while the laser diode is biased above or at the threshold, an amplifier with cutoff characteristics is required. Otherwise, the laser diode should be biased below the threshold. The optical input power at the "ON" to "OFF" transition point $P_d$ is given by

$$c_2P_d = I_c - c_1k(I_b + I_s - I_{\text{th}}) + I_s/A. \tag{7}$$

Thus, the hysteresis width of optical input power for $I_b \geq I_{\text{th}}$ is $(c_1kI_s - I_s/A)/c_2$. The width of hysteresis increases with increase of $c_1k$ and $A$, and it is proportional to $I_s$.

It is well known in previous studies that to get optical bistability using semiconductor light-emitting devices, photodiodes, and electrical active elements under optoelectronic feedback, the cutoff and the saturation characteristics of the devices are required, as well as the amplification. The cutoff characteristic is necessary for the "OFF" to "ON" transition of the bistable device and it is usually implemented by the threshold characteristic of the laser diode (LD) [4] or its equivalent feature obtained by connecting a resistor in parallel to the light-emitting diode (LED) [5]. Therefore, the bias current of the laser diode must be smaller than the lasing threshold current. However, here we use the cutoff characteristics of a transistor. It improves the speed of the optical bistable device since biasing the laser diode above the threshold helps its high-speed operation. The amplification and the saturation characteristics are required for the regenerative amplification and the "ON" to "OFF" transition, respectively. They are achieved by electronic active elements such as transistors and avalanche photodiode.



(a)

(b)

(c)

Fig. 3. (a) Optical amplification, (b) optical bistability, and (c) optical thyristor characteristics of the realized bistable device. They are achieved by changing the closed-loop gain. Horizontal scale and vertical scale are $\sim 2$ $\mu$W/div and $\sim 40$ $\mu$W/div, respectively.

As shown in (3) and (6), the transition threshold level from the "OFF" state to the "ON" state depends on $R_b$ and the reverse transition threshold is obtained by the resistance $R_c$. By varying the resistance $R_c$, we can tune the optical output power of the bistable device and the "ON" to "OFF" transition point simultaneously. This tuning characteristic will be utilized to realize optical multistability.

In the experiment, a light-emitting diode and a phototransistor are used instead of an LD and a photodiode, respectively. The conversion efficiency $k$ of the light-emitting diode is about $1/40$. The gain of the phototransistor compensates for the reduction of the conversion efficiency, and makes the closed-loop gain larger than the unity for optical bistability. Measured optical output versus optical input characteristics of our bistable device are shown in Fig. 3. By tuning the closed-loop gain less than one, we obtained optical amplifier characteristics in Fig. 3(a). Measured optical gain is about 300. Fig. 3(b) shows optical bistability achieved with the closed-loop gain larger than one. As we increase the closed-loop gain, the bistable width that is the difference of the optical input power between the "OFF" to "ON" transition point and the "ON" to "OFF" transition point increases. If the closed-loop gain is larger than the upper limit in (5), the device has no "ON" to "OFF" transition as shown in Fig. 3(c).

## III. Optical Multistability

Optical multistability has been demonstrated by parallel connection of two bistable devices [3] and a twin strip laser diode with optoelectronic feedback [2]. By using the graphical solution method and the stability analysis given in this paper, new optical multistable devices may be designed. It is possible to realize optical multistability by incorporating optoelectronic feedback to the bistable laser diode or by using bistable optoelectronic feedback network and a laser diode. However, we choose a much simpler scheme; optical multistability is realized by using a laser diode and optoelectronic feedback network with a staircase transfer function.

We show the required transfer function and the graphical solution in Fig. 4(a). The straight line represents (1), i.e., the feedback current versus the optical output of the laser diode with a fixed bias current at the lasing threshold. The staircase curves are required for the feedback current versus the optical output characteristics of the feedback network. The staircase characteristics are easily realized by summing the piecewise linear curve of (2) with different values of $I_c$. In other words, the feedback current of the multistable device is

$$I_f = \sum_{i=1}^{n} I_{fi}(I_{si}, I_{ci}) \tag{8}$$

where $I_{fi}$ denotes the feedback current of each stage that may be expressed by (2) with the saturation and the cutoff current $I_{si}$ and $I_{ci}$, respectively. It is also assumed that $I_{ci} > I_{cj}$ for $i > j$. With increase of the optical input power, the staircase curve shifts to the left and generates new solutions, either stable or unstable. The optical output versus the optical input in Fig. 4(b) that is derived graphically shows optical multistability since the negative slope portions are unstable steady-state solutions. The stability is checked by using (4). If each stage of the feedback amplifier has the same characteristics (i.e., $I_{si} = I_s$ for all $i$, and $I_{ci} = i \times I_c + (i - 1)I_s/c_1A$), the condition for optical multistability is given by

$$I_s \frac{c_1kA - 1}{A} < I_c < I_s \frac{m+1}{m} \frac{c_1kA - 1}{A}. \tag{9}$$

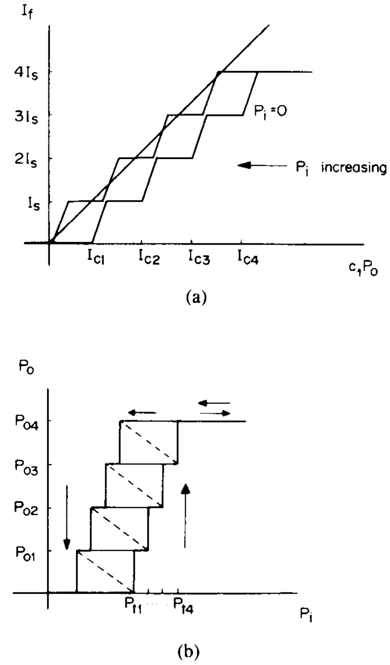
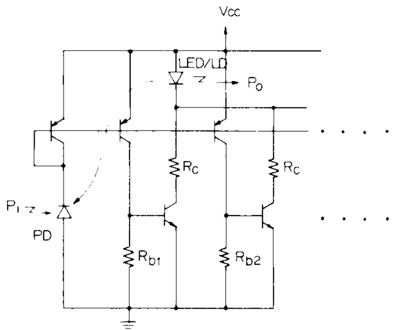


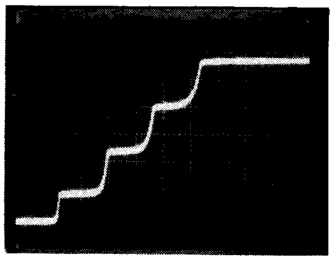

Fig. 4. (a) Graphical solution of the optical multistable device with $I_s$ = 1 mA, $I_{c1}$ = 0.5 mA, $c_1$ = 0.5, $k$ = 1 mW/mA, and $A$ = 3. (b) Optical output versus optical input characteristics of the optical multistable device. $P_{t1}$ and $P_{o1}$ are 1 mW.

The condition for the closed-loop gain, $c_1kA$, is given by (4). The lower limit in (9) is the condition of a sequential "ON" transition following the order of the magnitude of $I_{ci}$. The upper limit in (9) is the condition of multistability with $(m + 2)$ stable states at the same optical input. For large $m$, both limits coincide. If this upper limit is not satisfied for $m = 1$, the multiple bistable loops are achieved. Thus, we may get two devices by changing $I_{ci}$ (or $R_{bi}$) only. It is also possible to realize optical multiple multistable loops by changing $R_{bi}$. These features explain the good tuning capability of our multistable device.

To explain the physical mechanism of this device, we assume the bias current of the LD is equal to its lasing threshold current. The laser diode emits no optical output until the input optical power is equal to $P_{t1} = I_{c1}/c_2$ (i.e., the photodiode current reaches the cutoff current of the amplifier). With an increase of the input optical power, the transistor amplifies the photodiode current and the LD emits the optical output and it is fed to the photodiode. The photodiode current is amplified regeneratively if the closed-loop gain is larger than one. It drives the transistor to saturation and the optical output becomes constant or $P_{o1} = kI_s$. This is the first "ON" transition in the multistable curves. By increasing the optical input power further, it becomes $P_{t2} = I_{c2}/c_2 - c_1P_{o1}/c_2$. Then, the second "ON" transition occurs, and so on. At the $l$th "ON" transition point, the optical input power is $P_{tl} = I_{cl}/c_2 - c_1(l - 1)P_{o1}/c_2$. As we decrease the optical input power, the "ON" state is maintained until the sum of the optical input power and the increased feedback optical output




(a)



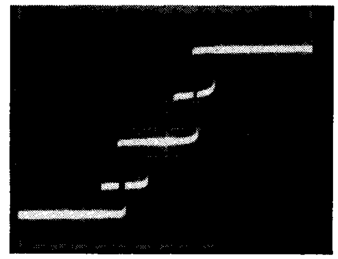
(b)

Fig. 5. (a) Circuit diagram of the optical multistable device. (b) Measured feedback current versus optical input characteristics of the realized optical multistable device. Horizontal scale and vertical scale are $\sim 25$ $\mu$W/div and $\sim 40$ $\mu$W/div, respectively.

power reaches the required optical input power at the transition point from the "OFF" to "ON" state plus $I_s/A$. In other words, the optical input power at the "ON" to "OFF" transition point of the $l$th "ON" state $P_{dl}$ is given by $P_{dl} + c_1 P_{ol}/c_2 = P_{tl} + I_s/c_2 A$. The width of the hysteresis is $(c_1 P_{o1} - I_s/A)/c_2$.

The circuit diagram of an optical multistable device is drawn in Fig. 5(a). The device consists of an LD, a photodiode, and transistors. An amplifier with staircase characteristics is realized by the photodiode and transistors. A pair of p-n-p and n-p-n transistors form a basic stage of staircase curve. The p-n-p transistors are employed to implement a simple current mirror [9] and the photodiode is connected to the collector of the source transistor of the current mirror. We use the current mirror for proper isolation of each stage. Assuming every transistor of the current mirror has the same characteristics, the current through one arm of the current mirror is equal to that of photodiode. Therefore, the circuit is equivalent to parallel connections of the bistable devices shown in Fig. 1(b) with variable transition thresholds $I_{ci} = V_\gamma/R_{bi}$. Use of the current mirror, instead of an individual photodiode, offers some advantages. First of all, the problem of aligning photodiodes to a single LD is removed. And, in view of integrating devices, a transistor occupies less area than a photodiode. By varying the base resistance $R_b$, the transition point of the device or the optical output power versus optical input power characteristics may be tuned arbitrarily. This feature is important in realizing various types of devices.

(a)



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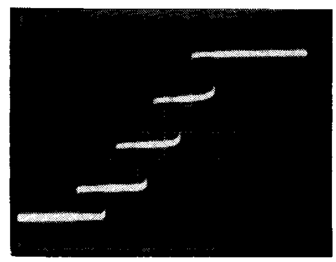

(c)

Fig. 6. (a) Measured optical multistable characteristics. (b) Measured optical multiple multistable loop characteristics. (c) Measured optical multiple bistable loop characteristics. They are achieved by changing the cutoff current of each stage. Horizontal scale and vertical scale are $\sim 5$ $\mu$W/div and $\sim 40$ $\mu$W/div, respectively.

In the experiment, a phototransistor and a light-emitting diode are used instead of an LD and a photodiode. Fig. 5(b) shows staircase characteristics of the feedback current versus the optical input when the optoelectronic feedback loop is open in our multistable device. By incorporating optoelectronic feedback, we realized optical quinstability, multiple multistable loops, and multiple bistable loops, as shown in Fig. 6(a), (b), and (c), respectively. We obtain these types of characteristics by changing the $R_b$, as was discussed. Since we use an ordinary oscilloscope with a simple scan of the optical input, intermediate states in the closed multistable curve are not shown in Fig. 6(a). The unequal width of the hysteresis for each state is due to nonuniform values of $h_{FE}$ of transistors and $R_b$-dependent gain as noted in (3). The unequal height between the states comes from the nonlinearity of the phototransistor. It is important to note that the dark current of the photodiode and the open-base collector-to-emitter current $I_{ceo}$ must be considered to obtain proper values of the resistance $R_b$. To get the optical multistable device with equal widths of hysteresis, the decrease of the gain due to the resistance $R_b$ should be compensated for, even if the transistors have the same characteristics.

If we use as the input the electrical signal instead of the optical signal, the optical output versus the bias current characteristics show multistability. This function is required for interfaces between optics and electronics. Multistable solutions in this case are also found by the graphical solution method. With the staircase curve fixed, the straight line moves up and down as the bias current decreases and increases from the threshold current, respectively. The conditions imposed on the cutoff of the amplifier and the upper limit of the closed-loop gain are relaxed. However, the upper limit on the closed-loop gain appears if the saturation current of the amplifier is larger than the threshold current of the laser diode.

## IV. Discussion and Conclusion

The demonstrated multistable device operates at submilliwatt optical input power. For example, a calculation based on practical values of device parameters indicates that the optical input power at the first "OFF" and "ON" transition point, or the switching power, is about 0.1 mW for the system constructed with silicon transistors, a laser diode biased at the lasing threshold, and $R_{b1}$ of 6 kΩ. The optical output power $P_{o1}$ is 1 mW for $I_s$ of 1 mA. Thus, the power consumption of all transistors in the "ON" state of our multistable device is about the same as its optical output power. The laser diode with 10 mA threshold current requires about 20 mW power consumption for threshold biasing. Since the most power is consumed in the laser diode, a laser diode with a low threshold current is required to reduce power consumption and thermal problems. A single quantum well laser diode with submilliampare threshold current [11] will reduce the power consumption to about 1 mW.

It is possible to reduce the switching time of optical multistable devices by using high-speed elements. The switching time of a photodiode is on the order of 10 ps. And a GaAs metal semiconductor field-effect transistor (MESFET) or high-electron mobility transistor (HEMT) has about the same order of switching time, while the laser diode has a switching time of 100 ps. Thus, the switching time of our device is limited by that of the laser diode. However, there is a problem in realizing it. For transistors operating in the saturation region, stored excess charges in the base region cause a serious delay time in the "ON" to "OFF" transition. This delay time increases the "ON" to "OFF" transition time of the multistable device and also reduces the repetition rate. To overcome this problem, nonsaturated operation of transistors is desired. By using a Schottky clamped transistor or a emitter coupled logic (ECL) scheme, this saturation problem may be solved. And the use of another current mirror instead of the collector resistor $R_c$ in Fig. 5 may also overcome the speed limitation due to the saturation of transistors.

The optical bistable and multistable devices proposed in this paper may be also realized by using field-effect transistors as an amplifier. In this case, the amplifier acts as a voltage-to-current converter with gain. The APD and photoconductive detector will be used as an amplifier to realize the devices. However, the bias current of the laser diode must be smaller than the lasing threshold current.

The proposed device is basically an extension of the ordinary electronic logic to the optical logic. By going to optics, we can take many advantages of optics, e.g., parallel processing capability and extremely wide interconnection bandwith. Since the most chip area of the large-scale integrated circuit is occupied by interconnection wires, optical interconnections may become valuable even in the intrachip level.

The proposed device works for any input polarization and a very wide range of input wavelengths. It has submilliwatt switching power and a fast switching time. Most of all, it has a large optical gain enabling cascade operation, excellent tuning capability, and hard limit characteristics. These attractive features may be useful for basic elements in optical digital signal processor, as well as electrical-to-optical (or optical-to-electrical) signal converters in optical interconnection units, optical repeaters, and analog-to-digital converters. There are also several disadvantages. This multistable device is complex as compared to the intrinsic one, and it is not easy to achieve a two-dimensional array. However, advances in surface emitting laser diodes [10] offer the possibility of a two-dimensional array of the proposed devices. And use of an ultralow threshold laser diode such as the quantum well laser diode [11] will reduce power consumption and switching time.

In conclusion, we have demonstrated optical bistability and optical multistability using a light-emitting device, a photodiode, and transistors. By tuning the cutoff current of each stage, optical multiple bistable and multistable loops characteristics are realized. Also, their operation principle and high-speed operation scheme are described.

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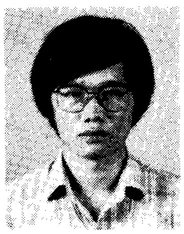

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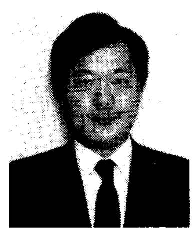

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