Multistate Self-Electrooptic Effect Devices

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Abstract—**We analyze and demonstrate novel multistate self-electrooptic effect devices (M-SEED's) containing several quantum well diodes in series. We show that a device with N diodes in series with a voltage source and illuminated by N light beams has N stable states corresponding to any one (and only one) of the diodes being highly transmissive. We show that this voltage-biased M-SEED can perform contention resolution in the sense required by analog systems because the diode illuminated by the weakest beam becomes the highly transmitting one on powering up the system. We further show that a current-biased M-SEED with N diodes in series with a current supply can have 2^N stable states, corresponding to any combination of diodes in their "transmitting" or "absorbing" states. This same device can also function as a binary image thresholder. Importantly, these M-SEED's are multistable in multiple beams, in contrast to previous multistable optical devices that have multiple states for one beam. We also demonstrate electrically and optically enabled symmetric SEED's (S-SEED's) that comprise a pair of quantum well p-i-n diodes in series with a transistor or a third diode. This device is the equivalent of an electrical "tristate" device that is used in some bus architectures.**

I. Introduction

OPTICAL bistability is a subject that has attracted much interest in recent years [1], both for its fundamental interest and for possible applications in digital signal processing. The classic optically bistable system will have two possible stable transmission states for a given range of optical input powers in a single light beam. Many of these such devices have been proposed.

One attractive class of optical devices for optical processing applications is the quantum well self-electrooptic effect device (SEED) [2]–[11]. The SEED can have low operating energy densities, it can be fabricated in two-dimensional arrays, and many types of SEED's performing a variety of functions have been proposed and demonstrated. SEED's utilize quantum well (QW) material to modulate the power of an incident light beam through the quantum confined Stark effect (QSCE) [12]. In particular, SEED's with single QW diode can show simple single-beam optical bistability [2], [3]. The concepts underlying single-beam bistability have been extended by many authors to single-beam multistability (see [1] for a review), in which there can be more than two stable states for a given optical input power. Such phenomena have been seen with single QW diode SEED's [3].

SEED's can also be designed to operate with more than one input light beam, opening up a further range of options in optical devices. The first such device was the diode-biased SEED (D-SEED) [3]–[5], in which the bistable switching threshold for one (infrared) beam can be set with another (visible) light beam, and the visible light beam can also switch the device. The D-SEED employed one QW diode and a conventional photodiode. Recently, we have demonstrated a symmetric SEED (S-SEED) that is bistable in the ratio of two (infrared) light beam powers and uses two QW diodes [9]–[11]. The S-SEED has many attractive features for systems applications, including insensitivity to power supply fluctuations and gain without critical biasing, features that were difficult to achieve with single-beam bistable devices. Cascadable logic gates have recently been demonstrated with S-SEED's, as have photonic ring counters [10].

In the present paper, we are extending the S-SEED concept to multiple-beam multistable devices (M-SEED's) using several QW diodes. It is important to emphasize at the outset that the multistability we discuss here is very different in character from single-beam multistability because the situtations we will discuss use multiple beams, a kind of multistability not previously demonstrated in optical devices to our knowledge. In this case, there are only two possible states for each transmitted beam, "on" (high transmission) or "off" (low transmission), but there are many such beams and hence many possible states of the system as a whole. In general, therefore, we will be considering N beams incident on the N elements of our device. Such a system could have a very complex set of possible states. We will show here that there are simple sets of conditions allowing well-defined operation as devices with either N or 2^N stable states, and we will demonstrate these behaviors experimentally for the simplest nontrivial cases. A consequence of the N state device is that it can be used to find the weakest of N beams, a function that may be of interest for contention resolution in neural networks [13]. The 2^N state device can be used for controllably thresholding an entire image. In this device, the optical transmission of each element is "high" unless the optical input power exceeds a threshold set by a constant current source, in which case the transmission is "low." We will also demonstrate other configurations that operate as optically gated S-SEED's.

II. Voltage-Biased M-SEED's

We will first analyze the states with N illuminated quantum well diodes in series with a voltage source (Fig. 1).

Manuscript received September 20, 1988; revised March 2, 1989.

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IEEE Log Number 8928477.

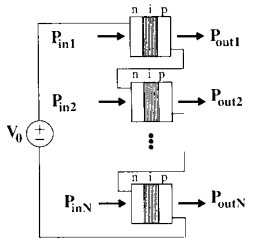

Fig. 1. Voltage-biased M-SEED. FOR $N = 2$, this is the symmetric SEED (S-SEED.).

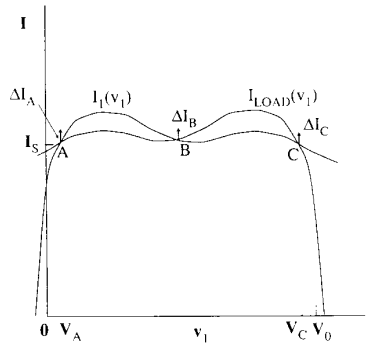

Fig. 2. Stability of the S-SEED. V_1 is the voltage across the first quantum well p-i-n diode, $I_1(v_1)$ is the current generated in the first quantum well diode, $I_{LOAD}(v_1)$ is the current generated in the rest of the circuit (i.e., the second quantum well diode and the voltage source), ΔI_A, ΔI_B, and ΔI_C are the changes in current of the first diode with an increase in the optical power incident on that diode starting at equilibrium points A, B, and C, respectively.

We will find that for equal illumination, the only stable states are with one and only one diode "on" (high transmission), and the others "off" (low transmission), and we will demonstrate this experimentally. We will also show how this device can be used to find the weakest of N beams. Then we will discuss and demonstrate optically enabled S-SEED's with three such diodes, and electrically enabled S-SEED's with two diodes and a transistor.

To analyze one quantum well diode in a circuit, we simply graph the current–voltage characteristic of the quantum well diode together with the current–voltage characteristic of the rest of the circuit as a "load line." The intersections of one with the other determine the equilibrium states whose stability depends on the response of the system to a small perturbation, for example, in the power incident on the quantum well diode. If after this perturbation the deviation of the system for equilibrium grows even more strongly, then the equilibrium is unstable. If, conversely, the system merely settles to a new equilibrium in the same vicinity, then the equilibrium is stable.

Fig. 2 shows the graphical solution for two voltage biased serially connected quantum well diodes (i.e., the symmetric SEED) for the case of equal incident powers P_{in_1} and P_{in_2} on each diode (solid curves). $I_1(v_1)$ is the current–voltage characteristic of diode 1, and $I_{load}(v_1)$ is the current–voltage characteristic of the rest of the circuit (i.e., diode 2 in series with the power supply). Immediately after a sudden small increase in P_{in_1}, the current in the first diode is shown by the dashed line in Fig. 2. At point A, we now find an excess current ΔI_A in diode 1. This tends to reduce V_1, hence reducing I_1 (and hence ΔI_A). Hence, point A is stable. A similar argument holds for point C, which is also stable. At point B, however, the opposite is true; as V_1 tends to decrease because of the excess current ΔI_B, the separation between the dashed curve and $I_{load}(V_1)$ (i.e., ΔI_B) increases, until equilibrium is reached at point A. Therefore, point B is unstable.

The extension of this argument to the case of many quantum well diodes in series with a voltage source is straightforward also, provided that we note one principle; for a state to be stable, it must be stable for all diodes. Consider the state with one diode "on" and all other diodes "off" with equal illumination on all diodes. This situation is depicted in Fig. 3(a) for diode 1 being "on." We have only plotted that portion of the load curve that corresponds to the state in question. Because there are several diodes in series, with all the others being in forward bias, V_D is essentially the sum of all the forward bias voltages of the other diodes, and is consequently larger than was V_C in Fig. 2. The slope of I_{load} against voltage may also be somewhat shallower because we now have the sum of the slope resistances of several diodes. These details notwithstanding, point D for diode 1 is clearly a stable operating point. Fig. 3(b) shows part of the corresponding curves for diode 2 (one of the "off" diodes). I_{load} in this case corresponds to that of one "on" diode with all other diodes "off." Here, clearly, point E is stable. We obtain graphs identical to those of Fig. 3(b) for each of the other "off" diodes. Hence, the state corresponding to one diode "on" and all others "off" is stable for identical diodes and equal powers.

For two diodes "on" and the rest "off," again with equal powers, the resulting curves are shown in Fig. 3(c) I_{load} may be somewhat steeper in slope than the corresponding curve in Fig. 2 because of the series slope resistance of the "off" diodes, and is shifted to the right by the forward bias voltages of the "off" diodes, but it is clear that point F is unstable. Hence, the state with two diodes "on" is unstable. States with more diodes on will generate curves of a similar form. Hence, the only stable states of this system are those with only one diode "on." (The state with no diodes "on" is also possible if the supply voltage is such as to correspond to all diodes forward biased, but this is a trivial case.)

For completeness, we can give a general procedure for calculating the stable states of any SEED with equal or unequal beam powers, even if the SEED contains other components such as a series resistor. For a given set of input powers, first choose a current I_s; second, note the voltages possible for each device for that current. For example, for the characteristic $I_1(V_1)$ in Fig. 2, the two possible voltages are V_A and V_C for current I_s. We must repeat this step for all series currents. Third, to find the equilib-

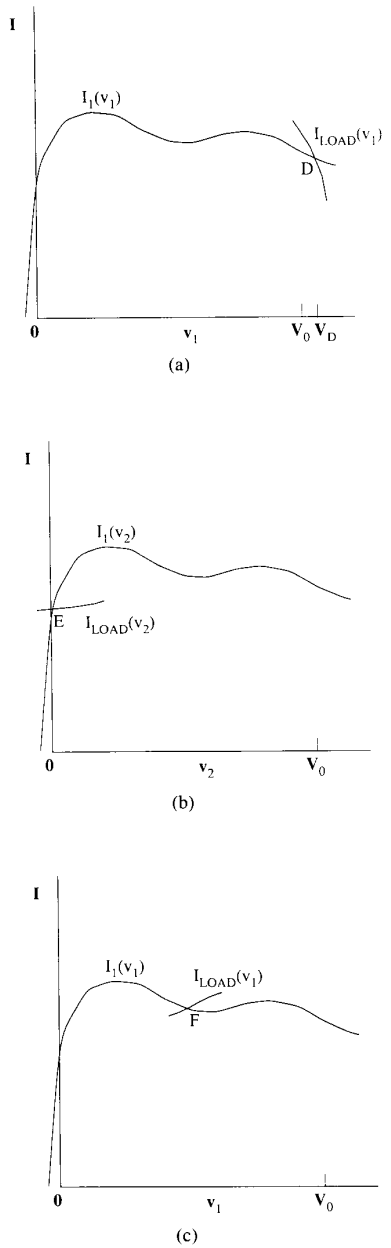

Fig. 3. Stability of N diodes in series with a voltage source. (a) First diode "on," others "off." (b) Second diode "off." (c) First and second diodes "on."

rium states, retain all combinations of these voltages at a given current that add up to the supply voltage. Finally, we can find which states are stable by the procedure outlined in Fig. 2. Other series components, such as resistors, photodiodes, or transistors, can be included by adding their effects in the overall "load" curve for the rest of the circuit in each case.

The input/output characteristics for this multistate device using three quantum well p-i-n diodes in series with a voltage source were measured using one S-SEED connected electrically in series with a single p-i-n diode that was part of another S-SEED on another chip. The devices used here were described in [9]–[11]. An integrated version of the device could be easily made using the identical layer structure and processing as the S-SEED except with three such mesas instead of two. The three curves in Fig. 4 show the three optical output powers as a function of the optical input power on the first QW diode measured at 856 nm (the excitonic peak at zero volts bias). In Fig. 4(a) the power of the input beams into the second diode was slightly greater than that into the third. In Fig. 4(b), the glass slide was inserted and the power of the third was slightly greater than the second. No states were found that correspond to two of the diodes being "on" (reverse biased) at once.

So far, we have considered the stable states themselves. Now, let us examine how the various states can be achieved. It is clear that this system has hysteresis. Once the device is in a given stable state, small perturbations of any of the beam powers will not change the state. However, if one (say the pth) of the beam powers is lowered below the (previously) weakest beam by some critical factor $1/k$, switching will take place so that this pth device will switch "on" leaving all others "off." Given a knowledge of all the device characteristics and all the beam powers, we could calculate k using the general procedure given above.

Consider the three-diode case shown experimentally in Fig. 4. Assume that the input power levels are approximately equal, and that the initial state is with the first diode "on" and the other two diodes "off." Increasing the power into the first diode so that it is at least a factor of k greater than the power on the other diodes will switch the first diode in the "low" state and one of the other two diodes (the one with the lowest power) in the "high" state. This is shown in Fig. 4 for the cases where the power incident on the second diode was slightly greater [Fig. 4(a)] and slightly less [Fig 4(b)] than the power incident on the third diode. Conversely, lowering the input power on the second diode at least a factor of k below the other two powers will switch the second diode in the "high" state and the first diode in the "low" state. (The third diode remains in the low state.) This is also shown in Fig. 4(b) if we interchange the labels of the first and second diodes. Similarly, the power in the third diode can be reduced, resulting in that diode switching "on." This is shown in Fig. 4(a) if we again interchange the labels on the first and third diodes.

As we have shown above, there is hysteresis in the response of the device to optical inputs. For the device to set the QW diode with the weakest beam to its "on state," the current input with the least power must be less than the other inputs by a significant amount; otherwise, the device state does not indicate the weakest beam. A solution to this problem is to momentarily set the supply voltage to 0 V. If the input signals are now applied while ramping the voltage back to V_0, the input signals only need to differ by a small amount (to overcome noise) to switch the device to the desired state. This follows from the sta-

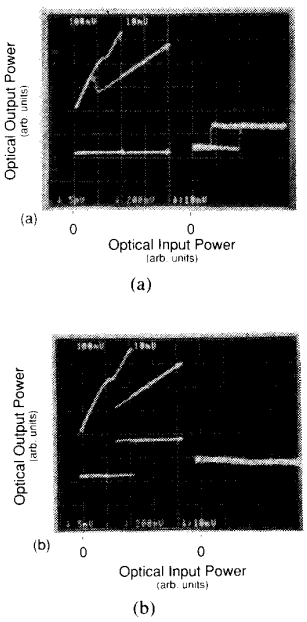

Fig. 4. The top left, bottom left, and bottom right traces are the optical powers of the beams exciting from the first, second, and third diodes, respectively, as a function of the input power incident on the first diode. (a) Optical power of light incident on the second diode is slightly greater than that incident on the third diode. (b) Optical power of light incident on the third diode is slightly greater than that incident on the second diode.

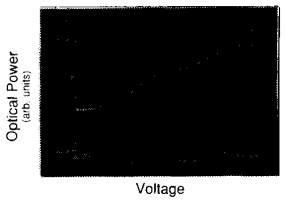

Fig. 5. Optical power of the output beam exciting from the first p-i-n diode as a function of the terminal voltage on two serially connected p-i-n diodes with constant optical input powers. Flat curve corresponds to the case when the power incident on the first diode is slightly greater than the incident on the second diode. Sloped curve corresponds to the reverse case.

bility argument above since the diode with the weakest incident optical power will have the largest reverse voltage across it as the supply is ramped up from 0 V. We have demonstrated this for two diodes connected to a voltage source (i.e., the S-SEED). The "flat" trace in Fig. 5 shows the optical transmission of the first diode as a function of the voltage across the series pair for the case when the optical power in the first diode is slightly more than in the second diode (by ~ 4 percent). In this case, the transmission as a function of voltage is constant, indicating that the voltage across the first diode is constant and essentially all the supply voltage appears across the second diode. The other trace in Fig. 5 shows the optical transmission of the first p-i-n diode for the case when the optical power in the first diode is slightly less than that in the second diode (by ~ 4 percent). In this case, the transmission changes as a function of voltage, indicating the supply voltage is present across the first diode. Therefore, we have shown experimentally that there is no hysteresis loop when the state of the device is set while ramping the voltage up from 0 V to a final value (i.e., V_0) and that the p-i-n diode with the least incident optical power has a voltage across it approximately equal to the supply voltage and has high optical transmission, hence performing contention resolution with the *weakest* beam winning.

The voltage-biased M-SEED's retain the desirable attributes of the S-SEED [9]–[11], which is a special case of these devices for $N = 2$. The switching point of these devices is determined by the ratios of the powers of the incident light beams on each diode, so the device will be insensitive to laser power fluctuations, provided that all beams are derived from the same source. We can operate both the S-SEED and M-SEED with time sequential gain where the state of the device can be set using relatively low-power beams, and subsequently read out using high-power beams of nearly equal powers. Momentarily setting the supply voltage to zero when the signal beams are applied allows beams with only a small difference in power to set the state of the device since it will select the weakest beam for high transmission as the voltage is turned on. This is an additional gain mechanism that also applies to the S-SEED. In addition, this time sequential operation gives input/output isolation because the large output signal never coincides in time with the application of a small input signal. Thus, these voltage-biased M-SEED's avoid the problems of critical biasing in multistable devices as well.

An alternative to turning the supply voltage off and on when setting the state of the device is to use an $(N + 1)$th element that is controllably either conducting or effectively insulating. This could be another quantum well diode illuminated by a strong "enabling" beam or it could be an electronic gate such as a transistor. For the case when $N = 2$, this device is an enabled S-SEED as shown in Fig. 6(a). For an enabled S-SEED, when the power in the enabled input is much less than the power in the signal beams, the two "signal" outputs will have low transmission. Such an enabled device behaves in a fashion analogous to the tristate devices often used in electronic buses. Such electronic devices can be actively "on," actively "off," or disabled (high impedance) so that many of these many such devices can be connected in parallel on an electronic bus, with only one device active at a time. A similar system can be operated with the enabled S-SEED, with the Q and $\overline{Q}$ outputs of all such S-SEED's summed optically, for example, at the input to another S-SEED. The sense (i.e., greater or less than 1) of the resulting ratio of the two sums of the output signals would be determined by one device that was enabled, as would the resultant state of the summing S-SEED.

In another experiment, a discrete silicon n-p-n transistor replaced one of the quantum well p-i-n diodes in the enabled S-SEED [Fig. 6(b)] demonstrating an electronic enable function that behaves similarly to the optically en-

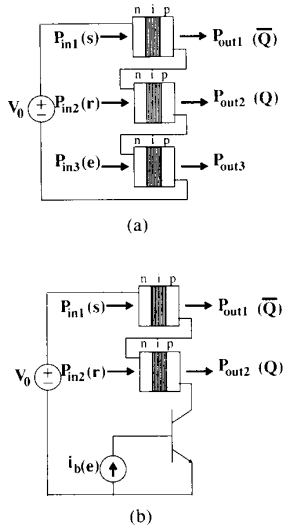

Fig. 6. Enabled S-SEED with optical (a) and electrical (b) enable functions.

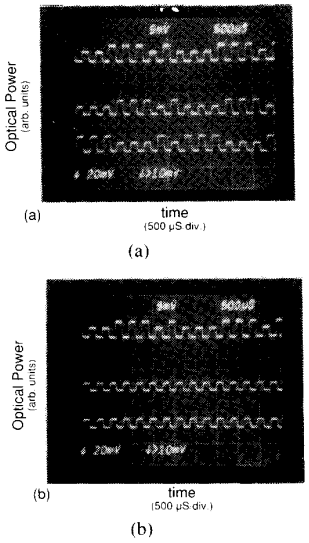

Fig. 7. One of the complementary input signals (top trace) and both output signals (bottom traces) from an electrically enabled S-SEED. (a) Base current of ~200 nA. (b) Base current of ~0 nA.

abled device described above. The signal inputs to the two quantum well p-i-n diodes of the device consisted of the complementary outputs from a previous S-SEED differential modulator [11]. A set of two clock beams of roughly equal amplitude subsequently read out the state of the device. Fig. 7 shows one of the complementary inputs and both of the outputs from the electronically enabled S-SEED with either zero [Fig. 7(b)] or a few hundred nanoamperes [Fig. 7(a)] flowing into the base of the transistor.

III. Current-Biased M-SEED's

If we replace the voltage source in the voltage-biased M-SEED with a current source (Fig. 8), each p-i-n diode

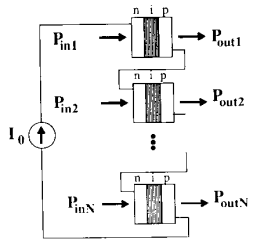

Fig. 8. Current-biased M-SEED.

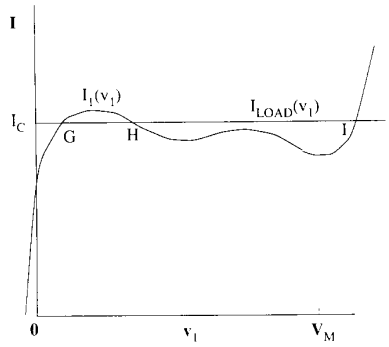

Fig. 9. Load line representation of current-biased quantum well p-i-n diodes.

acts as an independent optically bistable device. This may be explained as follows. In practice, the actual current-voltage characteristic of the diodes may be of the form shown in Fig. 9 if the voltages are sufficiently high. The eventual upturn of the current at high voltages can be caused by avalanche breakdown of the diodes or could be arranged by the introduction of a parallel Zener diode or even a parallel resistor across each quantum well diode. For sufficiently high supply voltages (greater than approximately $Q \times V_M$), it will be possible to have Q diodes "on" simultaneously. Following the same argument as for Fig. 2, points G and I in Fig. 9 are stable, and point H is unstable. With point G corresponding to "off" and point I to "on," both of these states are stable for a given diode, independent of the states of the other diodes because the "load" current is constant (e.g., I_C). Thus, with N diodes in series with a current source, there can be 2^N stable states, which is equivalent to storing an N bit word.

To test this, we connected a 12 V Zener diode across each p-i-n diode in the S-SEED. As a current source, we used a 200 V power supply in series with a 20 MΩ resistor. Using two current-modulated laser diodes at 855 nm with average optical power levels incident on each diode of ~30 μW, we show the optical output power as a function of the respective input power on each diode in Fig. 10. There are two truly independent bistable loops. The modulation rate of each laser was ~2 Hz, but we could vary either one of them separately and not affect the other one. When only one of the diodes was modulated, we could switch the unmodulated p-i-n diode, but only over a very narrow range of optical power levels incident on

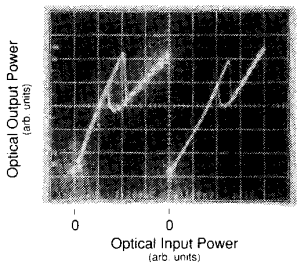

Fig. 10. Input/output characteristics of current-biased M-SEED. Left curve is the output power versus respective input power on the first p-i-n diode and the right curve is the output power versus respective input power on the second p-i-n diode.

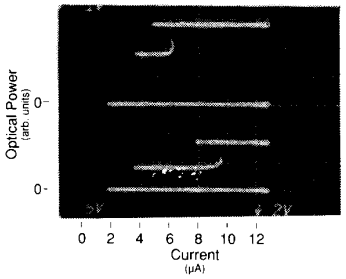

Fig. 11. Output power of current-biased M-SEED as a function of constant current. The incident optical powers of the two input signals were ~ 18.2 and ~ 25.7 μW for the top and bottom traces, respectively, and the current was measured by looking at the voltage across a 1 MΩ series resistor. Horizontal lines are baselines for the traces above them.

the unmodulated diode, and then only if the modulation rate were sufficient. Perhaps this was caused by the fact that we did not have a "true" current source or by some capacitive cross coupling in these integrated devices. By slowing down the modulation rate below 0.1 Hz, this effect could not be found.

The setting of the states in such a current-biased SEED operating at a particular current is straightforward. When the power in a given input beam exceeds a certain threshold determined by the operating current, the associated element turns "off." It can then be turned "on" by reducing the power below another threshold as shown in Fig. 10. The states of the device can also be set by ramping the current up progressively from zero. Each element will start in its "off" state, only turning "on" when the current passes the threshold set by optical power incident on the QW diode. Hence, if we have a large number of elements, we can "digitize" the transmission of the image with the threshold set by the operating current. That is, those elements with incident powers less than the threshold will be "on" and all others will be "off." The threshold here is set by a single current, rather than by an array of light beams as in previous SEED thresholding devices [5]. We have demonstrated this by using the same S-SEED described above with Zener diodes connected in parallel across each p-i-n diode. The device was connected to a variable voltage source varying sinusoidally from 0 to 173 V at 0.25 Hz through an 11 MΩ resistor. For relatively large voltages, this still approximates a constant current source. The results are shown in Fig. 11. The incident optical powers of the two input signals were ~ 18.2 and ~ 25.7 μW for the top and bottom traces, respectively, and the current was measured by looking at the voltage across a 1 MΩ resistor (included in the 11 MΩ resistance above). The current thresholds for switching "on" were ~ 6.2 and ~ 9.6 μA for the two inputs and the switching "off" transitions occurred at ~ 4.8 and ~ 7.8 μA. The constant current source could have been varied optically as opposed to electrically by adding an $(N + 1)$th diode that has a constant responsivity as a function of voltage and a high reverse breakdown voltage (such as a standard photodiode) in series with a voltage source with a voltage greater than the sum of all the breakdown voltages of the QW diodes.

IV. Conclusion

We have described and demonstrated several novel multistate self-electrooptic effect devices (M-SEED's) consisting of several (say N) series-connected reverse-biased quantum well p-i-n diodes. These devices differ from earlier multistable devices that have multiple states for a single beam in that these devices are multistable in multiple beams; that is, each transmitted beam has only two states, but the resulting device has either N or 2^N states. The voltage-biased M-SEED can perform contention resolution in that it can select the input signal with the least optical power. An M-SEED with three such diodes is an optically enabled symmetric SEED that is equivalent to tristate electronic devices used in bus architectures. We have also demonstrated an electrically enabled S-SEED by replacing one of the three diodes with an n-p-n transistor. By biasing the N diodes with a current source, we have also demonstrated a device that has 2^N stable states and can store an N bit word. The device can function as a binary image thresholding device where the transmission of a particular diode is "high" only if the incident optical power on the diode is less than a threshold determined by the constant current.

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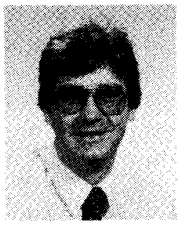

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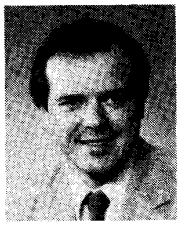

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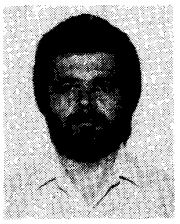
Dr. Cunningham is a member of the American Physical Society.



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