

Symmetric self-electro-optic effect device: Optical set-reset latch

A. L. Lentine and H. S. Hinton

AT&T Bell Laboratories, Naperville, Illinois 60566

D. A. B. Miller, J. E. Henry, and J. E. Cunningham

AT&T Bell Laboratories, Holmdel, New Jersey 07733

L. M. F. Chirovsky

AT&T Bell Laboratories, Murray Hill, New Jersey 07974

(Received 10 December 1987; accepted for publication 15 February 1988)

We demonstrate an integrated symmetric self-electro-optic effect device consisting of two quantum well *p-i-n* diodes electrically connected in series. The device acts as a bistable optical memory element with individual set (*S*) and reset (*R*) inputs and complementary outputs (optical *S-R* latch). The switching point is determined by the *ratio* of the two inputs, making the device insensitive to optical power supply fluctuations when both power beams are derived from the same source. The device also shows time-sequential gain, in that the state can be set using low-power beams and read out with subsequent high-power beams. The device showed bistability for voltages greater than 3 V, incident optical switching energy densities of $\sim 16 \text{ fJ}/\mu\text{m}^2$, and was tested to a switching time of 40 ns.

The potential use of optics in telecommunications switching and computing has generated considerable interest in recent years. One approach is to use planar two-dimensional arrays of logic or memory devices interconnected with free-space optics. One proposed class of devices uses Fabry-Perot étalons containing semiconductor nonlinear refractive materials.¹⁻⁴ Uniform operation over different areas of the resonator³ and fast switching times⁴ have been demonstrated. Another device is the quantum well self-electro-optic effect device (SEED).⁵⁻⁸ SEED's rely on changes in the optical absorption that can be induced by changes in an electric field perpendicular to the thin semiconductor layers in quantum well material. This effect has been called the quantum confined Stark effect (QCSE).^{9,10} Combining the QCSE with optical detection within the same structure can cause optoelectronic feedback and bistability. Uniform arrays of bistable integrated diode-biased SEED's (D-SEED's)⁷ as large as 6×6 (Ref. 8) have been demonstrated.

A problem with optically bistable systems is that, to obtain the gain necessary for cascaded logic, the devices need to be biased very close to their switching transition. Such critical biasing imposes very strict tolerances on the uniformity of the devices and the bias beam powers. One solution is to operate an étalon (without bistability) with two wavelengths.^{3,11} This requires two different devices, one to down-convert and the other to up-convert wavelengths. The device that we demonstrate here, the symmetric SEED (S-SEED) is optically bistable, but is bistable in the *ratio* of two beam powers, rather than any absolute power. When both beams are derived from the same source, source power fluctuations are, therefore, unimportant. Furthermore, the device does not need to be biased close to a switching point to give gain, so that uniformity of bias beams is not critical. It can show time-sequential gain by being switched at low power and read out at high power. Such time-sequential operation also gives good input/output isolation, because a small reflection back onto the device will not change its state. Hence this device offers a potential solution to some of the major problems of optical bistability for logic.

The D-SEED previously demonstrated^{7,8} consists of a

p-i-n diode with quantum wells in the intrinsic region vertically integrated in series with another photodiode that is used for the load. The load photodiode is transparent to the wavelengths used for the quantum wells ($\sim 850 \text{ nm}$) but absorbs all of the incident light for wavelengths less than 750 nm. When a He-Ne laser is used to "bias" the photodiode load, the array behaves as a set of nearly identical bistable devices whose switching power and speed can be set over many decades by adjusting the intensity of the He-Ne laser. In addition, the array can operate as a dynamic memory where the state of the device is preserved when both the bias and the infrared beams are removed. The stored state may be read out sometime later (up to 30 s) by simultaneously increasing the two beams.⁸ In the symmetric SEED, the load is a second *p-i-n* diode with multiple quantum wells in the intrinsic region. Since the two diodes are identical, either diode can be considered as the load of the other. The basic physical mechanisms in the D-SEED and the S-SEED are therefore similar, but the ability to work with two complementary beams at the same wavelength greatly increases the usefulness of the S-SEED.

The schematic diagram and physical layout of the device are shown in Fig. 1. The material was grown by molecular beam epitaxy on a Si-doped *n*-type GaAs substrate. The *p* region was grown as a fine-period GaAs/AlGaAs superlattice as in the integrated D-SEED to improve the quality of the material. The structure, which is *n-i-p-i-n*, results in two back-to-back diodes between the substrate and the top *n* regions. The multiple quantum well *p-i-n* diodes (on top) are connected "horizontally" by an external connection rather than "vertically" during growth as in the D-SEED, circumventing the problem that limited the speed of the D-SEED, namely, the limited current that could be carried by the internal ohmic contact in that structure. The isolation diodes (bottom), comprised of the AlGaAs *i* and *n* and superlattice *p* regions, ensure electrical isolation between the *p* regions of the two quantum well diodes. In operation, both of the isolation diodes are always reverse biased by connecting the substrate to a positive voltage. The quantum well diodes are made by etching separate mesas and electrically connected

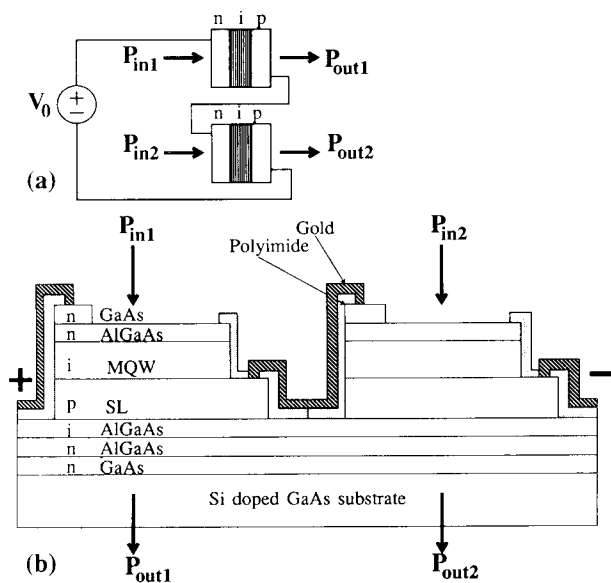


FIG. 1. Symmetric SEED: (a) schematic diagram and (b) physical layout (not to scale). The Al mole fraction in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ is 0.4. Epitaxial layer thicknesses and dopings (from bottom to top): n -GaAs ($0.17 \mu\text{m}$, $n = 10^{18} \text{cm}^{-3}$); i -AlGaAs ($1.92 \mu\text{m}$); p -superlattice (SL) (250 periods of alternate 25 \AA AlGaAs and 21 \AA GaAs, $p = 10^{18} \text{cm}^{-3}$); i -multiple quantum wells (MQW) (63 periods of alternate 80 \AA AlGaAs and 105 \AA GaAs layers); n -AlGaAs ($0.64 \mu\text{m}$, $n = 10^{18} \text{cm}^{-3}$); and n -GaAs ($0.105 \mu\text{m}$, $n = 10^{18} \text{cm}^{-3}$). Both the GaAs substrate and the GaAs buffer layer are removed by a selective etch under the device active area.

using ohmic contacts and evaporated gold over a polyimide insulator. The mesas are $\sim 200 \mu\text{m} \times 200 \mu\text{m}$ on $400 \mu\text{m}$ centers, and the optical window is $\sim 100 \mu\text{m} \times 200 \mu\text{m}$. The substrate is cleaved into separate 1×2 arrays that are packaged individually. The electrical connections to the device are made using silver epoxy to hold the bond wires to the gold metallization. The GaAs substrate and buffer layer are etched away underneath the optical windows, and an antireflection coating is applied.

The operation of the device can be understood through the use of load lines as shown in Fig. 2. By solving for the voltages across the quantum well diodes as a function of the two input power levels, we can determine the optical transmission of the two diodes and hence the input/output characteristics. As shown in Ref. 6, the device is bistable when

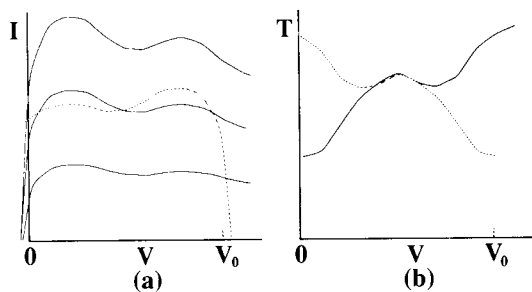


FIG. 2. Characteristics of both quantum well diodes. (a) Solid curves are the photocurrent vs voltage for a quantum well diode at three different input intensities. Dashed line is the photocurrent on the load quantum well diode vs voltage on the first quantum well diode for an input intensity on the load diode equal to that incident on the first diode in the middle curve. (b) Solid curve is the transmission vs voltage for the first quantum well diode. Dashed curve is the transmission of the load quantum well diode vs the voltage on the first diode.

there are three intersection points, and this will only occur if we operate the device at a wavelength where there is a region of decreasing absorption (and therefore decreasing current) for increasing voltage. Furthermore, the device will only be bistable when the optical input power levels are comparable, and will have only a single state when the power in one diode greatly exceeds the power in the other. Figure 2 also shows that if we increase (or decrease) the optical input power levels into both devices by the same factor (for example doubling both input power levels) or by the same fixed amount, the voltage at which the current-voltage curves intersect will not change, and hence the state of the device will not change. This allows us to set the state of the device using low-power beams of different intensities and then read out the state of the device using higher-power beams of equal intensities, thus achieving time-sequential gain.

The measured input/output characteristics of the device shown in Fig. 3 agree with the calculated results using the method described above. The characteristics were measured using an argon-ion-laser-pumped styryl 9 dye laser, although some measurements were also made using a com-

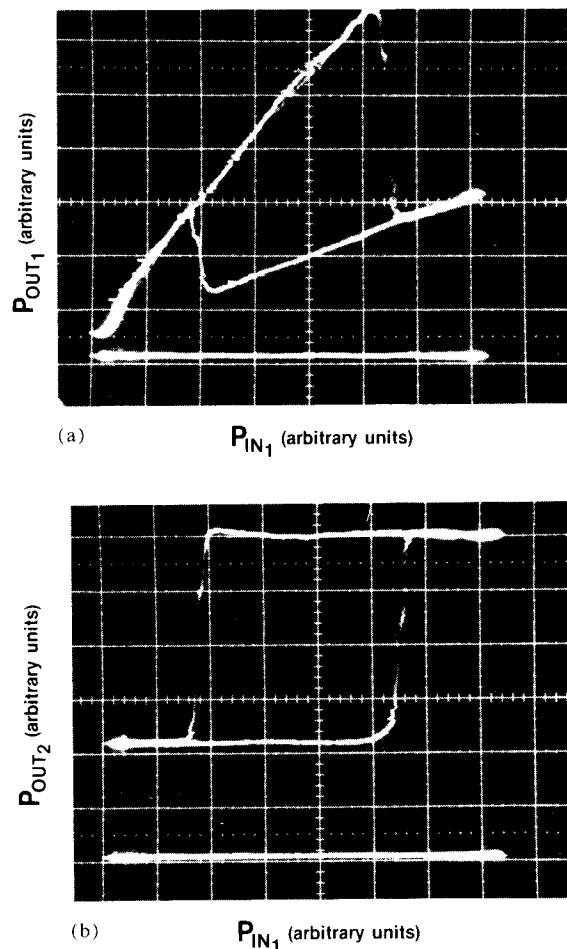


FIG. 3. Optical input/output characteristics of the S-SEED measured at a supply voltage of 15 V at 856 nm with average input power levels of $\sim 20 \mu\text{W}$. (a) Optical power exciting first diode (P_{out_1}) vs optical power incident on first diode (P_{in_1}) with the optical power incident on second diode (P_{in_2}) held constant. (b) Optical power exciting second diode (P_{out_2}) vs P_{in_1} with P_{in_2} held constant. Optical transmission levels are $\sim 41\%$ and 14% for the two states shown in the figure.

