Quantum well optical tri-state devices

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We demonstrate quantum well tri-state logic devices for possible use in optical bus architectures. These optical devices are analogous to the tri-state devices often used in electronic buses, where each device can be actively on, actively off, or disabled with at most one device on the bus active at a time. We show two methods of generating these tri-state data, one using tri-state quantum well modulators and one using optical tri-state self-electrooptic effect devices, and we demonstrate a simple optical bus consisting of two such devices. Finally, we comment on the limitations on the number of devices that can be connected to a bus of this type.

Key words: Quantum wells, optical interconnections, optical computing, SEEDs.

Lately, there has been much interest in the use of optics for performing signal processing functions as well as interconnecting electrical circuits.[1] Advantages of optics are well known: they include the independence from interconnection length, lack of interference between connections, interconnection bandwidth, and the ability to do many interconnections in parallel. It has even been shown that optics can perform interconnections more energy efficiently than electronics for all but the shortest distances.[2] Most devices that are proposed for these interconnections are single ended input/single output devices, whose logic decision is based on a comparison of the data input to a fixed reference. The main drawback with the use of these single ended devices is that tight tolerances are required on the powers of the optical beams to make the correct logic decision. The use of differential devices, where the logic state is defined by the ratio of the powers in two light beams, avoids the need to provide a threshold and thus makes building systems easier. The symmetric SEED[3] (S-SEED) which consists of two quantum well PIN diodes connected electrically in series is an example of such a device. Like all SEEDs,[4,5] the S-SEEDs make use of the change in optical absorption of quantum well material with a change in an applied electric field perpendicular to the wells by way of the quantum confined Stark effect.[6] By incorporating the quantum wells in a detector, in this case in the intrinsic region of a reverse biased diode, we can have optoelectronic feedback and bistability, which can be used for these all-optical logic devices. The S-SEED has some desirable attributes from the standpoint of optical processing systems design. The device has time-sequential gain in that the state of the device can be set using low power beams and subsequently read using higher power beams. Because the inputs and outputs occur at different times, it has input–output isolation. It provides signal retiming because the input data are latched and then clocked out with a correctly timed robust clock signal, and the switching of the device is controlled by the ratio of the two input beams making it insensitive to power supply fluctuations when both beams are derived from the same source. By modulating the voltage on the center node of the device, we can modulate two light beams in a complementary fashion,[3] an application of which is to interconnect electrical circuits. Although the S-SEED can act as a differential detector as well,[3] more sophisticated differential detector circuits that can interface directly with MOS logic devices have been designed.[7] By using a combination of these detector circuits and S-SEED differential modulators for interconnecting electrical integrated circuits,[7] these systems retain the attributes described above for the S-SEED.

The S-SEED can be extended to three (or more) diodes in series.[8] This device can perform as an optical tri-state SEED [Fig. 1(a)], analogous to the tri-state devices often used in electronic buses. Such electronic devices can be actively on, actively off, or disabled

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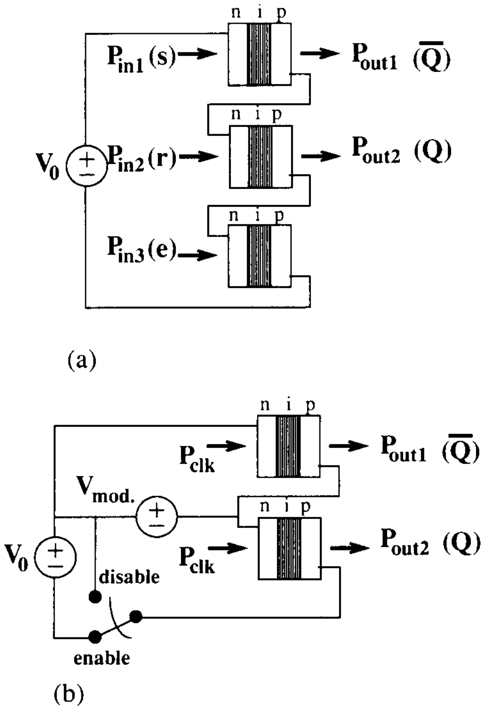

Fig. 1. Tri-state optical devices: (a) tri-state SEED for use in all-optical systems; (b) tri-state quantum well modulator. (V_{mod} should be set to zero when disabled.)

(high impedance) so that many such devices can be connected in parallel on an electronic bus with at most one device active at a time. For the optical device, a strong beam on the enable input effectively shorts that diode thus enabling the remaining two diodes to act as an S-SEED, which has two states dependent on the ratio of the power of the two input beams. A weak beam on the enable input effectively disables that diode setting both outputs of the remaining S-SEED to an inactive low state. An optical bus can be made by summing the Q and $\bar{Q}$ outputs of many tri-state SEEDs optically, for example, at the input to a differential detector. The sense (i.e., $\gtrless$ than 1) of the resulting ratio of the Q and $\bar{Q}$ sums of the output signals would be determined by the one device that was enabled, as would the resultant output state of the differential detector. This differential detector could be a symmetric SEED, a tri-state SEED, or a more complex differential detector as described in Ref. 7. When interconnecting electrical circuits, the three logic states could also be synthesized by the use of a tri-state modulator as shown in Fig. 1(b). The incoming light beams can be modulated in a complementary manner by adjusting the voltage V_{mod} on the center node of the device, or both outputs could be set to a low power level by applying 0 V to each diode. A simple way to do this is to turn off the supply voltage and the modulation voltage, although many different configurations of this circuit are possible.[8] Thus the data coming from these tri-state modulators are of the same form as that which would have been generated by tri-state SEEDs in an all-optical system. We describe an experiment where the outputs from two of these tri-state modulators are combined as the input to a differential detector, which happened to be a tri-state SEED. This experiment is a simple demonstration of a tri-state optical bus as described above.

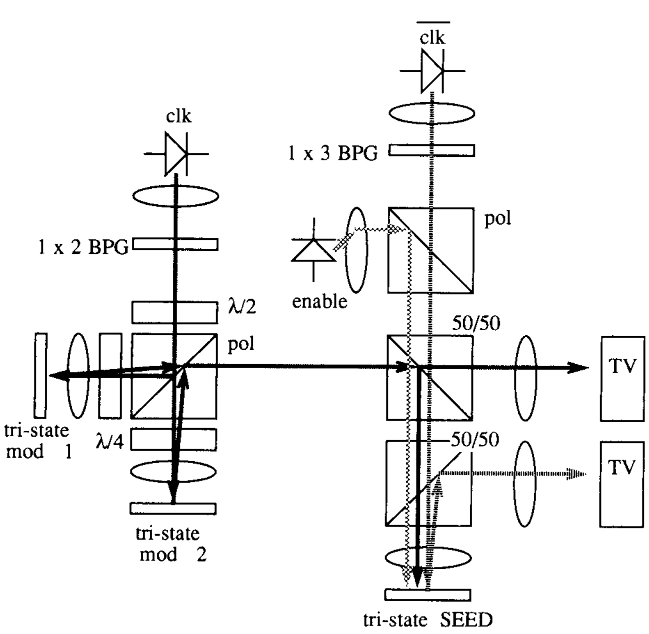

Fig. 2. Experimental setup for the optical bus. Arrows show the interconnections between devices and are not actual ray traces.

The devices used in the experiments were fabricated in a manner similar to the batch fabricated S-SEED arrays that have been previously reported.[9] The mesas were $\sim$300 μm^2 in area with two 10-μm diam round optical windows. The tri-state SEEDs were packaged as 2 × 6 arrays, and the modulators were packaged as 2 × 2 and 4 × 2 arrays. Characterization of the devices with an argon-ion pumped Styryl 9 dye laser showed that the best wavelength of operation was 848 nm, and the best contrast ratio was $\sim$5:1 at 15-V bias at that wavelength.

A block diagram of the optical bus experiment is shown in Fig. 2. The optical input to the tri-state modulators was a pair of square-wave modulated light beams generated by current modulating AlGaAs semiconductor laser diodes. After passing through the modulators, both sets of modulated data signals were combined using a polarization beam splitter and focused onto one of the windows on each of two mesas of the tri-state SEED, and an enable beam was focused onto the third mesa. A 1 × 3 binary phase grating generated the three equal power clock beams used to read the state of the tri-state SEED. These beams were focused onto the other windows of the three mesas.

The results of the experiment are shown in Fig 3. Only the noninverted data inputs S and noninverted outputs Q are shown. Figure 3(a) shows the outputs of the two tri-state modulators and the tri-state SEED in conditions where the first modulator is active and the

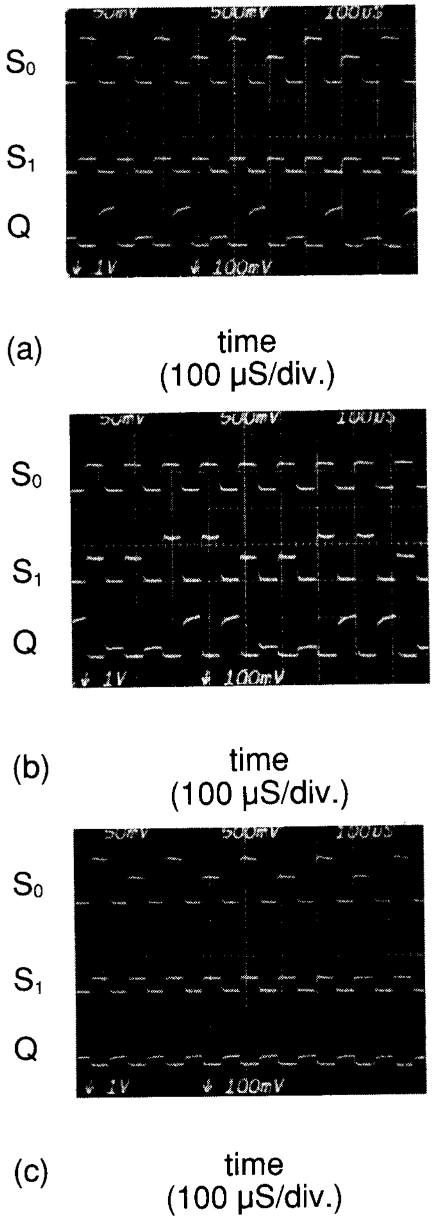

Fig. 3. Experimental results from the optical bus experiment. Top and middle traces are the Q outputs of the first and second tri-state modulators (S inputs to the tri-state SEED). Bottom trace is the Q output from the tri-state SEED. (a) The first modulator is active, and the second modulator is disabled. (b) The second modulator is active, and the first modulator is disabled. (c) The enable input power on the tri-state SEED is low. (Time-sequential operation is responsible for the time shift between the outputs of the modulators and the tri-state SEED.)

second is disabled. Figure 3(b) shows the reverse case. The outputs of the optical tri-state SEED are shifted in time relative to the inputs (i.e., the outputs of the modulators) because of the time-sequential operation of these devices. In Fig. 3(c), the enable input power on the tri-state SEED is reduced, and the output is low, regardless of the input data. (The $\bar{Q}$ output is also low.) The contrast ratio of the outputs from the tri-state modulators could be adjusted by adjusting their supply voltages. The optical bus was found to be operational with contrast ratios of the tri-state modulators as poor as 1.25:1 with 6-V bias on the tri-state SEED. For a bias of 15 V on the tri-state SEED, the contrast ratios of the modulators needed to be $\sim$1.4:1 for the circuit to function because of the increased width of the bistable loop. The output power levels of the tri-state SEED were $\sim$6 times greater than the input powers, demonstrating the same time-sequential gain mechanism as in the S-SEED.

The highest bit rate achievable in this experiment was $\sim$600 kbit/s, limited by the signal power incident on the tri-state SEED. The optical input power to each diode of the tri-state modulators was $\sim$950 μW, and the contrast ratio of the output signals was noticeably worse at this power than at lower powers, probably due to saturation of the quantum well material. Because of losses in the modulators and the interconnecting optics, the input powers to the tri-state SEED were $\sim$54 and 38 μW for the high and low states of a particular diode input. The calculated switching speed for the tri-state SEED, assuming that the required optical switching energy ($\sim$5pJ) is proportional to the difference in the powers of the two inputs (16 μW), is $\sim$312 ns. The slower switching speed that we measure here ($\sim$800 ns) is most likely due to the fact that the above assumption is invalid when the input contrast ratios are low. However, a quantum well reflection modulator has been demonstrated with switching speeds in excess of 5 GHz,[10] and silicon detectors and microwave amplifiers are readily available with speeds in excess of 10 GHz. Therefore, an optical tri-state bus can likely be extended to relatively high data rates.

The number of inputs that can be connected on the bus (i.e., the fanin on the input of the differential detector) is dependent on the contrast ratio of the active inputs and the required contrast ratio of the sum of all active and disabled inputs. Each disabled input contributes to an effective loss of contrast ratio of the overall input to the differential detector. For one active device with contrast ratio (CR) and $n - 1$ inactive devices, the overall contrast ratio at the input is $\{(\mathrm{CR} + N - 1)/N{:}1\}$. For example, if each output device has a contrast of 4:1 and we require the input contrast ratio to be 1.5:1 (to minimize tolerance problems, for example), we can have six inputs. For high contrast ratios, a large number of devices could be interconnected using a single optical bus. For lower contrast ratios, multiple stage networks would be needed. One method of increasing the number of devices that can be connected to the bus when using bistable SEED detectors is to ramp the supply voltage on the SEED up from zero while applying the data, effectively removing the bistable characteristics.[8] In this case the fanin will be dependent only on the tolerance (inequality) of the disabled devices. However, practical optical systems design, rather than device performance, may limit the fanin.

The limit on the width of the bus (i.e., how many bits are interconnected in parallel) is a function of the optics used for the interconnection and how many differential detectors and tri-state modulators can be integrated on the electronic chips. This question really has nothing to do with device performance. Several authors have stated that more than a thousand interconnections are possible using free-space optical techniques.[11] If each interconnection could work at 1 Gbit/s, this would correspond to a 1-Tbit/s optical bus.

In conclusion, we have demonstrated quantum well tri-state optical logic devices. These devices are analogous to electronic tri-state devices which can be active in one of two states or disabled (high impedance). These optical devices represent the logic state by the optical power in two output beams. The two active states are determined by which of the two output beams has the greater optical power, and the disabled state occurs when both output beams have low optical power. Both an optical tri-state SEED and a tri-state quantum well modulator have been used to generate tri-state data. A simple optical tri-state bus was demonstrated by using the output from two of these modulators to provide the data that were detected by a tri-state SEED acting as a differential detector. This experiment demonstrates the feasibility of a tri-state optical bus as a means for interconnecting electronic circuits or future photonic processors.

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