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Spatial light modulator and optical dynamic memory using a 6 × 6 array of self-electro-optic-effect devices

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Using a 6 × 6 array of integrated quantum-well self-electro-optic-effect devices, we demonstrate an optically addressed spatial light modulator able to convert a visible, incoherent image into coherent infrared (IR) light. Depending on the IR wavelength used, the output is either a positive, binary-thresholded version of the input (bistable mode) or its linear, negative (self-linearized) mode. This device can also function as a dynamic bistable memory that can retain its internal state without power for times as long as 30 sec.

Because of their exceptionally large electroabsorptive properties, quantum wells (QW's) are becoming the active material in an increasing number of electro-optic devices,[1,2] such as optical modulators, voltage-tunable detectors, and self-electro-optic-effect devices (SEED's). The integrated diode-biased SEED is promising for use in two-dimensional arrays of optical devices with low energy dissipation, with 2 × 2 arrays already demonstrated.[3] One important component for many optical processing schemes is the spatial light modulator (SLM) whereby either electrical or optical information can be imposed upon a coherent light beam. Although many such devices have been demonstrated,[4] improved performance is desirable. The use of QW's for SLM's has been proposed,[5–9] and electrically addressed SLM's have been demonstrated.[6,9]

In the present research we have used a 6 × 6 array of GaAs–AlGaAs QW integrated SEED's to demonstrate a simple, optically addressed SLM. Depending on the wavelength used, the device can be operated in its bistable mode, with switching times ranging between microseconds and seconds, or in its self-linearized mode capable of linearly following optical signals modulated with frequencies up to 240 kHz. We show that this device can also be used as a dynamic bistable memory, optically read and written, capable of holding its state for times as long as 30 sec without power.

The SEED[3,10] relies on the shift of the strong excitonic resonances in the absorption spectrum of QW's when electric fields perpendicular to the layers are applied, a mechanism called the quantum confined Stark effect (QCSE).[11] Combining the QCSE with optical detection within the same structure causes optoelectronic feedback that, when positive, can give optical bistability.[10] An optically bistable SEED consists of a reverse-biased diode containing the QW's and an electrical load (e.g., a resistor or a photodiode). The QW diode functions simultaneously as an absorption modulator and a detector. For incident wavelengths near the zero-field heavy-hole exciton absorption peak, decreasing reverse bias gives increasing absorption and photocurrent. The resulting voltage drop on the load further decreases the bias, increasing the absorption and the photocurrent even more. This positive feedback can lead to switching and bistability. At slightly longer wavelengths, where absorption decreases with decreasing reverse bias, the optoelectronic feedback is negative and the current flowing through the circuit is stable. Absorbed power becomes proportional to the drive current, giving self-linearized modulation.[10]

The integrated SEED structure used here is the same as in Ref. 3. The wafer consists of the following sequence of layers: N(substrate)–I–P–P^+–N^+–N–I–P–P^+. The lowest P–I–N diode contains in the intrinsic region 100 GaAs QW's (9.24 nm wide) separated by $Al_{0.35}Ga_{0.65}As$ barriers (6.13 nm wide). The upper P–I–N diode represents a load for the diode containing the QW's and is vertically integrated in series with it. The heavily doped P^+ and N^+ layers form an internal ohmic contact between the two P–I–N diodes. The P and N layers of the QW diode and the entire load diode are grown from GaAs/AlGaAs superlattice, which behaves essentially like the average AlGaAs alloy (effective $X \approx 0.21$). The upper P^+ layer is connected to a negative potential, while the N substrate is connected to a positive one, thus reverse biasing the whole structure. The voltages used here are 25 V for the bistable mode and 10 V for the self-linearized mode. The load photodiode is transparent to the IR wavelength at which the QW's operate (~0.85 μm) but absorbs essentially all wavelengths shorter than 0.75 μm. The structure is grown by molecular-beam epitaxy, and the devices are fabricated (contacts, masking, patterns, etching) by using the procedure described in Ref. 3. The 6 × 6 array of devices consists of 60 μm × 60 μm mesas (with 30 μm × 30 μm optical windows) spaced on 90-μm centers and has common top and bottom contacts to all devices. The total area of the 6 × 6 array is about 0.5 mm × 0.5 mm. Importantly, we

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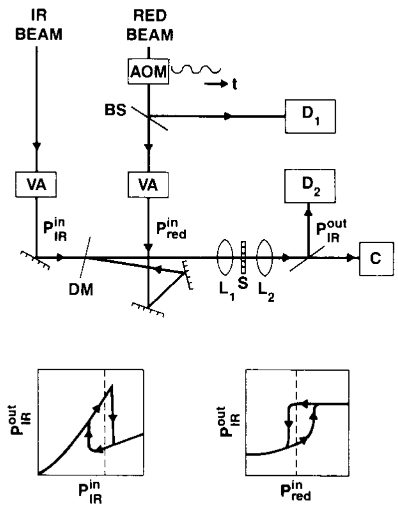

Fig. 1. Schematic experimental setup. IR beam from Styryl 9 dye laser. Red beam from He–Ne laser. AOM, acousto-optic modulator; VA's, variable attenuators; BS, beam splitter; DM, dichroic mirror (long pass); D1, silicon photodetector; D2, avalanche photodetector; L1, L2, 14-mm focal-length lenses, focused spot size ~15-μm diameter; C, television camera (mirror in front of camera is removed for viewing); S, sample. Insets: bistable loops obtained by ramping appropriate beam powers.

have found similar yields (~30%) of fully functional and uniform (within 10%) arrays for both the 2 × 2 arrays of 200 μm × 200 μm mesas (used in Ref. 3) and the present 6 × 6 arrays.

In operation two light beams are incident upon each device being tested: a visible control beam (absorbed in the top photodiode) and an infrared beam transmitted through the entire device. The optics depend on the particular application. Figure 1 describes the setup used to measure the input–output characteristics of each device. In the bistable mode, high IR transmission (ON state) corresponds essentially to the entire supply voltage's being across the QW diode, which is a result of the load photodiode's generating more photocurrent than the QW diode. OFF represents the opposite situation: low IR transmission, practically no voltage on the QW diode, and essentially all the voltage across the load diode, which is a result of the QW photodiode's generating more photocurrent than the load diode. Hence switching occurs when the ratio of the two photocurrents changes, and this can be achieved by varying either beam (see Fig. 1). We have checked this for λ_{IR} = 855 nm and IR powers ranging between 0.18 mW and 4.5 nW, with corresponding switching times ranging between 1 μsec and 40 msec. For a spot diameter of ~15 μm, these powers correspond to intensities ranging between 0.1 kW/cm^2 and 2.6 mW/cm^2. The switching energy (= switching time × switching power) is essentially determined by the electrical energy stored in the capacitance of either of the devices. It is a constant for a given device geometry and a given voltage, being roughly proportional to the area of the devices. We obtain ~180 pJ of power for these 60 μm × 60 μm devices, which should be compared with ~1200 pJ measured in the 200 μm × 200 μm devices of the 2 × 2 array.[3]

When these two bistable loops are used it is easy to understand how the device functions as an optical memory. Assume that the device is in one of its stable states corresponding to the particular pair of values (P_{IR}^{in}, P_{red}^{in}), as shown by the dashed lines on either of the two bistable loops in Fig. 1. By momentarily interrupting one or the other of the beams and turning it on again, one can change the state; thus the operating point can be set and reset *optically*, as has been observed before in discrete devices.[10] However, we additionally observe here that if both beams are interrupted simultaneously and then turned on again after a delay time, the device *retains its state* for delay times up to 5 sec for the 6 × 6 array and 30 sec for the 2 × 2 array. The explanation is that, without light, only the very low-leakage current changes the voltage on the device. Thus the device can operate as a memory, with very low average power consumption (≤250 nW/cm^2). Of course, in order to avoid accidental switching of the device when interrupting the beams, one should make the time taken to cut off both beams faster than the switching time corresponding to the operating point. We observed reliable memory of the previous state with cutoff times < 1/10 × the switching time.

This memory is behaving as a dynamic memory in that it retains its state with low average power, provided that it is periodically refreshed. In contrast to electronic dynamic memories, however, which require sense amplifiers to measure and refresh the charge in each cell, the entire optical memory can be refreshed in one clock cycle because no sense amplifiers are required. Although the internal voltage in the memory drifts because of leakage while the light is off, this drift is reset by the bistable action of the device itself when the light is turned on again (provided, of course, that the voltage has not drifted too far).

To illustrate the SLM mode of operation, a uniform IR illumination of the entire array has been achieved by adding a spatial filter and beam expansion in the

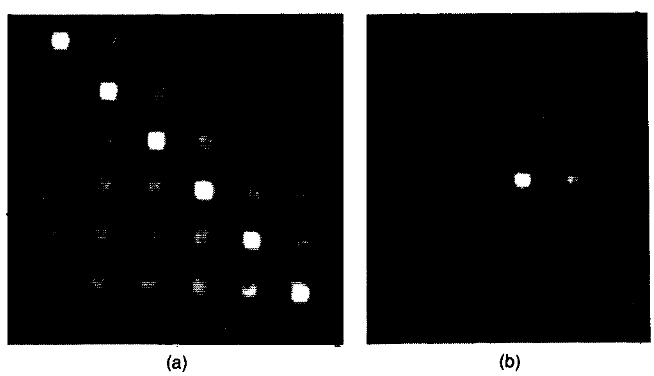

Fig. 2. (a) Transmitted IR output of the 6 × 6 array of integrated SEED's illuminated with uniform IR light (λ_{IR} = 855 nm) and with a visible incoherent image of a diagonal slit (visible source: tungsten lamp). (b) Illustration of AND operation: Resulting output when the array is illuminated with a horizontal IR slit image and a vertical visible slit image.

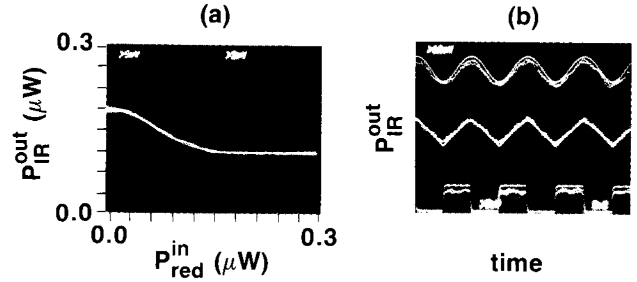

Fig. 3 (a) Optical transfer characteristic of a SEED device operated in the self-linearized mode (λ_{IR} = 859.2 nm). The horizontal line indicates zero transmitted power. (b) Time-modulated (80-Hz) IR output signal (noisy curves) compared with the red input signal (noiseless curves). The noise is due to fluctuations in P_{IR}^{in}. The traces corresponding to P_{IR}^{out} are inverted to ease their comparison with the traces corresponding to P_{IR}^{in}.

way of the IR beam in the setup described in Fig. 1. A visible image of a rotating slit illuminated by a light bulb was used instead of the red laser to switch the devices on. A binary thresholded version of the visible image appears on the transmitted IR beam, as shown in Fig. 2(a). If the image is removed, the devices will turn off again. If an image is also superimposed upon the incoming IR beam, the device performs an AND function between the visible and the IR images, as illustrated in Fig. 2(b).

The array can also operate as a linear SLM by running in the self-linearized mode,[10] in which the power subtracted from the IR beam is proportional to the incident visible light. This can be done by using a longer wavelength of the IR beam (λ_{IR} = 859.2 nm), for which the absorption coefficient of the QW's increases with increasing applied field and the optoelectronic feedback is negative. The optical transfer characteristic that one obtains is shown in Fig. 3(a). With increasing P_{red}^{in}, beyond a knee in the characteristic, the transmitted power decreases linearly with increasing control beam power, as expected. The reason for the knee is that the modulator has a minimum, nonzero absorption; once this minimum is reached the transmitted power cannot be increased further. At large P_{red}^{in} a second knee appears in the characteristic, after the self-linearized region; here essentially all the supply voltage is across the QW diode, and the absorption cannot be increased further. The ratio between the two flat regions in the transmitted power gives the maximum contrast that one can obtain: somewhat smaller than 2:1. Within the linear region we have checked the time-dependent transfer characteristics of the devices, and the results are illustrated in Fig. 3(b). The traces of Figs. 3(a) and 3(b) were taken using low input powers ($P_{IR}^{in} \sim 0.3$ μW), at which a maximum frequency of about 90 Hz can be used before distortion of the output signal appears. This upper limit can be increased by operating at higher optical powers, when the devices become faster: frequencies as high as 240 kHz can be used for optical powers of the order of 800 μW.

For practical SLM applications, the present 6 × 6 array is clearly still too small, although scaling to much smaller devices (e.g., 10 μm) is within the capability of the fabrication techniques. Such smaller devices would also be expected to have proportionate reductions in operating energies. Larger area arrays may also be possible with low defect density growth. The other principal limitation for SLM applications is the limited contrast ratio of modulation (~2–3.5:1). This could be improved by the use of integral reflectors[12]; in such modulators, contrast ratios as high as 8:1 have been observed. It is also still possible to increase the thickness of the QW region for further contrast-ratio improvements, as has been demonstrated.[7]

In conclusion, we have shown that arrays of SEED devices can be used as simple, optically addressed SLM's that convert an incoherent, visible image into a coherent, infrared one, either positive and binary thresholded or negative and linear, and also that the array can function as a self-refreshing optical dynamic memory with low average optical power consumption. It is also clear from this research that QW technology can deliver relatively large arrays of optical devices with novel functions, good yields, and performance that scales with area; that is particularly promising for future QW optoelectronic applications.

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