Linear image differentiation by use of analog differential self-electro-optic effect devices

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We demonstrate one-dimensional linear image differentiation, using an array of symmetric self-electro-optic effect devices with 64 × 32 elements. The device operates with pairs of power-supply beams. The spatial derivative, which may be of either sign, is given as the difference in the reflected output powers.

Quantum-well self-electro-optic effect devices (SEED's) are a class of optoelectronic devices consisting of p-i-n optical modulator diodes with quantum wells in the *i* region, combined with optical detection and possibly other electronic circuits, to give devices of many possible functions.[1,2] The simplest devices, which do not incorporate transistors, have been used mostly in digital applications operating at a wavelength approximately resonant with zero bias exciton (λ_0). In particular, the symmetric SEED (S-SEED) has been used for a variety of logic and optically bistable functions, operating with pairs of light beams.[3] The S-SEED can, however, also be operated as an analog device, as was recently proposed[4] and demonstrated.[5,6] In this mode the S-SEED is operated at a wavelength (λ_1) longer than the zero-bias-exciton peak and uses the difference between two light-beam powers to represent bipolar (positive and negative) analog values. Normally, processing such bipolar values is difficult with optics because the power in the light beam is always positive. This new differential circuit overcomes this problem and allows many different analog functions to be performed, including addition, subtraction, and spatial differentiation of images, correlation, and optically controlled bipolar matrix–vector multiplication.[4]

It is simplest to think of this class of analog differential device as having a set of conventional photodiodes (black box) as the optical signal inputs and a pair of quantum-well diodes driven by the net photocurrent from the conventional diodes as the output modulators (see Fig. 1). The functions performed by this device depend on the layout of the conventional photodiodes. For instance, if two similar conventional photodiodes, electrically in series, are physically aligned in the X direction, the net photocurrent from this circuit represents the local derivative d/dx of the incident intensity. If the device is rotated 90 deg (aligned with Y direction) it will now represent the operator d/dy. Here we demonstrate one-dimensional linear spatial image differentiation, using a pair of conventional photodiodes electrically in series and physically aligned in the X direction.

The symmetric SEED can be made in large two-dimensional arrays,[7] and it has already been used in experiments in free-space optical switching.[8] Previously[5,6] we demonstrated the functionality of this device, using only four optical beams, two of them incident upon the input conventional photodiodes and the other two as power-supply beams incident upon the quantum-well diodes. Here we use an array of 64 × 32 pairs of quantum-well diodes to demonstrate one-dimensional image differentiation.

The experimental apparatus that we used to perform the one-dimensional linear differentiation is shown in Fig. 2. It is similar to the arrangement used in a free-space optical switching experiment.[8] We used a symmetric SEED array with 64 × 32 series pairs of quantum-well diodes with diodes spaced by 20 μm. It was designed with an internal mirror to permit a double pass of the light through the active multiple quantum wells, increasing the output beam contrast. Each quantum-well diode has an approximately 7 μm × 7 μm optically accessible area and an antireflection coating to avoid Fabry–Perot effects. The fabrication steps and the layer structure are detailed in Ref. 7. A binary phase grating operating at 850 nm generated the 64 × 64 power beams,[9] and a special lens was used to focus them equally on the device. A polarizing-cube beam splitter was used to overlap the input image and the 64 × 64 power beams on the S-SEED. We used a pair of quarter-wave ($\lambda/4$) plates to adjust the polarization and obtain both the image and the array of beams on the S-SEED array. (Note that the use of the polarizing beam splitter together with the $\lambda/4$ plates and the 50:50 mirror does indeed allow the input to be imaged onto the SEED array, even though the input is initially reflected away from the SEED array.) To avoid seeing the nonabsorbed light image reflected from the S-SEED on the camera, we used a color filter in front of the CCD camera. The output image was recorded and acquired by a frame-grabber board on a PC.

A Ti:sapphire continuous-wave laser pumped by an Ar laser operating at 850 nm was used as source of the 64 × 64 control beams incident upon the quantum-well diodes. To generate the image we used a Hitachi diode laser operating at approximately 780 nm. We used polarized light to generate the image because it simplified the experimental setup, although this is not a necessary restriction.

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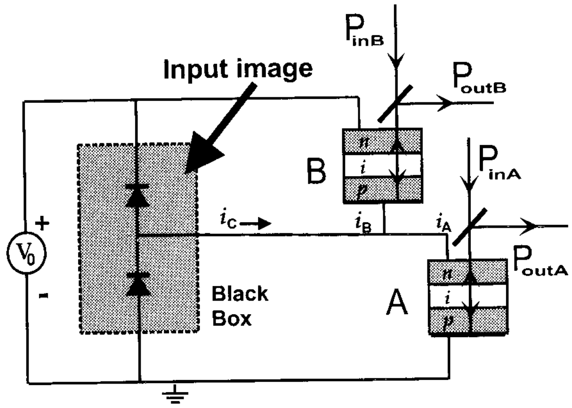

Fig. 1. Analog differential self-linearized circuit. The net photocurrent generated by any layout of conventional photodiodes (black box) drives the two quantum-well modulators, A and B. The pair of diodes inside the box is electrically in series and physically aligned to perform one-dimensional linear spatial image differentiation.

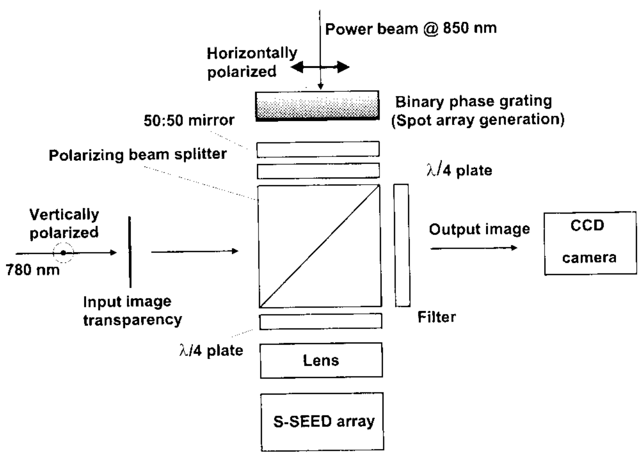

Fig. 2. Analog differential SEED setup used to make the linear spatial image differentiation.

The S-SEED two-dimensional array was not designed with conventional input photodiodes integrated on it. We used the same trick as in Refs. 5 and 6, operating the quantum-well diodes at a shorter wavelength, where their responsivity is approximately constant with respect to the voltage. (The same basic device concept will also work if the image is at 850 nm, although the linear dynamic range will be reduced,[6] and further measures are needed to separate the output beam array from the input image.) In this configuration the same pair of quantum wells is used as the input conventional photodiodes (when illuminated at 780 nm) and as the quantum-well diode modulators (when illuminated at 850 nm). The wavelength of 850 nm used in this experiment is resonant with the zero-bias-exciton wavelength in this device. However, for our experiment we need to operate at λ_1 (just below the zero-bias-exciton wavelength), so we cooled down the S-SEED to obtain λ_1 operation.

As an input image we used a transparency with the letter T at the wavelength of 780 nm. (The device is also able to handle input images with wavelengths in the visible range.) The pair of quantum-well diodes was aligned in the X direction, and therefore the net photocurrent available at the middle point between them will be equal to that in the d/dx operation.

Figure 3 shows the output at 850 nm from the symmetric SEED array, where the letter T is clear. In places where there is no image shining on the device, the voltage in each quantum-well diode of the pair is the same, and therefore the absorption in them is equal. Consequently both of the output beams have the same intensity. However, in the border of the letter T the intensity shining on each quantum well of the pair is different, resulting in different voltage across them and hence in different absorption. The absorption decreases for the diode where the intensity of the light is high because it generates more photocurrent than the other diode of a given pair, hence decreasing the voltage across the diode. In the other quantum-well diode of the pair the voltage increases (the absorption also), and therefore the output power decreases. In the center of the letter T the intensity is approximately the same, and therefore the outputs from the pair of quantum-well diodes are again equal. Note that the derivative takes place only in the X direction of the letter. To make the derivative in Y direction it is necessary to rotate the S-SEED array by 90 deg.

The derivative of the letter T is in fact the difference between the two reflected beams from each pair of quantum-well diodes. Figure 4 shows the result of this operation made in the computer, for which the image was acquired by a frame grabber. As we stated above, the important parameter is the difference between adjacent beams. From Fig. 4 we can see that in places where the image is constant (either bright or dark) the difference between adjacent beams is approximately zero, giving no derivative. In the border of the image there is a large enhancement of the difference. In the bottom of Fig. 4 the projection shows the differentiated letter T, where the bright area on left represents the positive derivative and the dark area on the right represents the negative derivative. In the middle the difference is

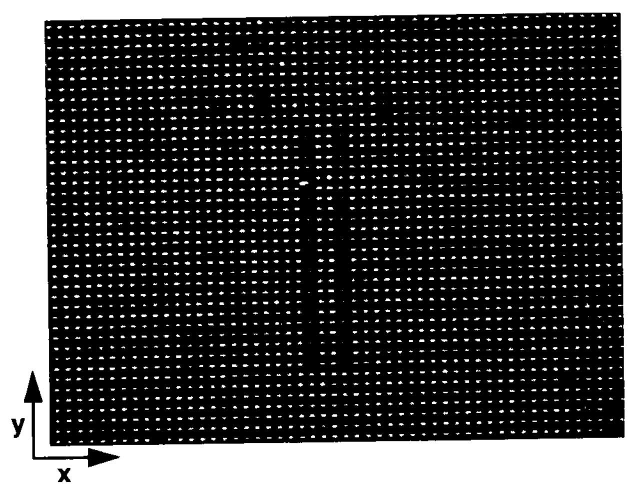

Fig. 3. Output image from the symmetric SEED array with 64 × 64 optical beams. The information (the linear derivative) is the difference between two horizontal adjacent beams. The input image (at 780 nm) shining on the 64 × 64 symmetric SEED array is the letter T.

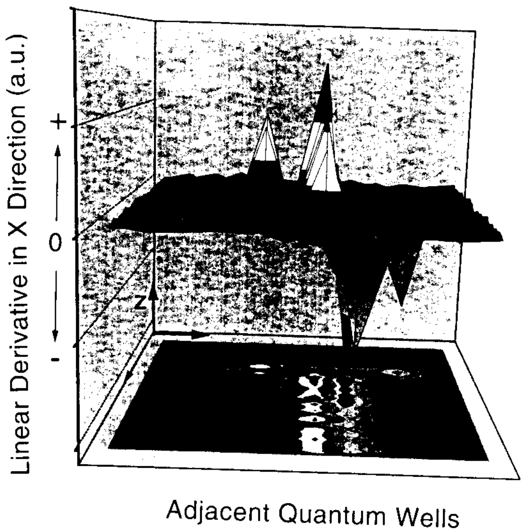

Fig. 4. Output image from the symmetric SEED array (64 × 64) after processing. Each point is the difference in intensity between two adjacent spots in the X direction.

zero, as expected. The output pairs of beams can in principle be used as bipolar analog inputs to subsequent analog processing stages.

The speed of the device depends on the power level shining on the modulators.[6] Higher speed is obtained by operation at higher power. The upper physical limits on speed are due to absorption saturation and finite carrier sweep-out time. The lowest speed is limited by the leakage current of the device. The present analog differential circuit can be analyzed by use of a simple linearized model in which the device is represented by a current source in parallel with a capacitor. For operation in a range where the absorption α in the quantum well changes approximately linearly with the voltage, for a small perturbation the circuit frequency response is given by $f = e\gamma P_{in}/2\pi h\nu C$, where e is the electronic charge, $\gamma = d\alpha/dV$ is the derivative of the absorption of the quantum well with respect to the voltage, P_{in} is the incident optical power, $h\nu$ is the photon energy, and C is the total capacitance of the device. From this expression we can see that the circuit runs faster for higher incident power and becomes slower for larger capacitance. With power levels used in the experiment (10–1000 pW incident upon the modulators), a capacitance of 5 fF, a factor γ of 0.06 V^{-1}, and an operating wavelength at 850 nm, the frequency response of the device is expected to vary from 15 Hz to 1.5 kHz for these powers. The speed of response was not tested in these experiments, but it has been characterized previously at speeds up to 10 MHz in similar structures.[6] One can run the device faster by increasing the incident power on the modulators. Hence this device is likely to be capable of processing at video rates and possibly significantly faster.

In conclusion, we have demonstrated the functional ability of the analog S-SEED to perform image differentiation in one dimension. This is a simple application of this smart circuit. Many complex functions could also be performed with more-complex designs, such as the Laplacian image transform. Work is in progress to demonstrate such functions.

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