Analog differential self-linearized quantum-well self-electro-optic-effect modulator

E. A. De Souza, L. Carraresi,* G. D. Boyd, and D. A. B. Miller

AT&T Bell Laboratories, 101 Crawfords Corner Road, Holmdel, New Jersey 07733-3030

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We describe an analog self-electro-optic-effect device that gives a difference between two optical output powers that is linearly proportional to electrical or optical drive, permitting bipolar processing in novel image-processing arrays. The device is able to operate over a range of more than four orders of magnitude optical power, from 50 nW to 2.5 mW, corresponding to uniform incident intensities as low as 3.3 mW/cm².

We demonstrate a new mode of operation for quantum-well self-electro-optic-effect devices (SEED's) by using their analog features. Our results show that this device is potentially useful for analog systems because it is linear in a range of more than 4 orders of magnitude (50 nW to 2.5 mW) of optical power, corresponding to uniform incident intensities of 3.3 mW/cm² to 200 W/cm². This device was recently proposed as a new analog SEED circuit operating with differential pairs of light beams.[1] It 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 circuit overcomes this problem and allows many different analog functions to be performed, including addition, subtraction, differentiation of image, correlation, and optical controlled bipolar matrix–vector multiplication.[2] In general, such functions operate on and generate both positive and negative values. This circuit permits full use of such values in analog systems, and, since it was fabricated by use of the symmetric SEED array process,[3] it is compatible with large two-dimensional-array fabrication techniques.

The key to this device is the use of a negative-feedback self-linearized mode of simple SEED circuits,[4] extended here to a novel circuit with two quantum-well modulator/detector diodes in series. The negative feedback arises when the absorption in the diode rises with increasing reverse-bias voltage. By choosing a photon energy just below the exciton energy at zero field, we can increase the optical absorption with increasing voltage as required, because the quantum-confined Stark effect shifts the band gap to lower energy.[5] As discussed previously,[4] when we drive a single illuminated quantum-well diode with a current source, the voltage across the diode adjusts itself to generate just enough absorption to give a photocurrent equal to the drive current. For example, if the diode were generating too little photocurrent, the net current would charge up the diode, increasing its absorption and hence its photocurrent. Since these diodes create one electron of current for every photon absorbed, the absorbed power is linearly proportional to drive current.

The present circuit (Fig. 1) implements the use of this mode with a pair of quantum-well diodes (A and B), reverse biased electrically in series, along with an electrically generated current I_c injected into the center point between the two diodes. In this case, applying the above self-linearizing principle together with conservation of current, we can deduce that the difference between the absorbed powers in the two quantum-well diodes is proportional to the drive current I_c injected into the center. This mechanism also works for an optoelectronic source for I_c (Fig. 2).

We characterized this circuit by using both current sources. For simplicity, we use equal input power shining on the quantum-well diodes ($P_{\beta B} = P_{\beta A}$), which results in zero offset. In the case of the photodiode-pair current source in Fig. 2, a current I_c flows out of the center point between the two conventional input photodiodes. The photocurrent in such conventional diodes is essentially independent of reverse-bias voltage and is therefore proportional to the difference between the absorbed powers in these two conventional diodes. If the difference between the incident power on the conventional diode 1, ($P_{\alpha 1}$), and the incident power on the conventional diode 2, ($P_{\alpha 2}$), is positive, the current flows out of the center point. By conservation of current, in the steady state the difference between absorbed powers in the two quantum-well diodes is linearly proportional to the difference between the absorbed powers on the two conventional diodes. If the conventional diodes pass

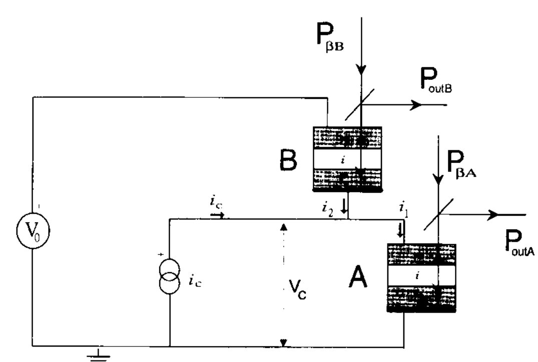

Fig. 1. Self-linearized differential modulator circuits with an electrical current source.

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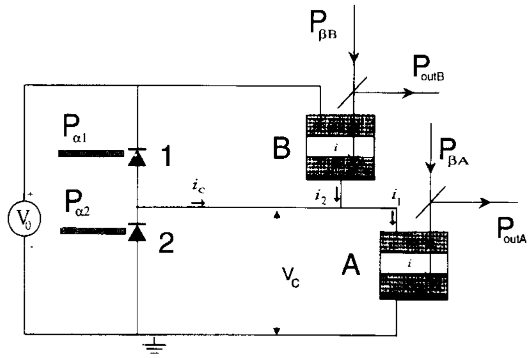

Fig. 2. Self-linearized differential modulator circuits with two conventional photodiodes providing a current proportional to the difference in input powers ($P_{\alpha 1} - P_{\alpha 2}$).

one electron of current for every incident photon, the difference between the output powers from the quantum-well diodes (P_{outA} and P_{outB}) can be equal to the difference between input powers shining on the conventional diodes ($P_{\alpha 1}$ and $P_{\alpha 2}$).

For these experiments we used a wavelength of 856 nm for $P_{\beta A}$ and $P_{\beta B}$ shining on the quantum-well diodes, which is longer than the exciton peak wavelength (850 nm) at zero field. The analog SEED structure used here is made by use of a standard symmetric SEED process and layer structure[4] and uses heterostructure layers of 10-nm GaAs wells with 3.5-nm barriers of $Al_{0.3}Ga_{0.7}As$ grown by molecular beam epitaxy. The structure consists of an undoped dielectric mirror, an n^+ conducting AlGaAs layer, a multiple-quantum-well region with 71 quantum wells, and a top p^+ conducting layer of AlGaAs. This design with an internal mirror permits a double pass of the light through the active multiple quantum wells, increasing the output beam contrast. Each quantum-well diode has an approximately 50 μm × 30 μm area and an antireflection coating to avoid the resonator effects. The fabrication steps and the layer structure are detailed in Ref. 3.

Figure 3 shows the individual output powers P_{outA} and P_{outB} from this circuit and voltage V_c at the center point between the two quantum-well diodes as a function of drive current I_c. As the drive current I_c is scanned from −1 to −1 μA, voltage V_c changes from approximately zero to as high as the maximum voltage applied to the circuit $V_0 = 8$ V. The voltage V_c is, in fact, the voltage applied on quantum diode A (see Fig. 1). If it is low, the voltage applied on the other quantum diode, B ($V_0 - V_c$), is high, and vice versa. When V_c is high (8 V) the output power from quantum diode A (P_{outA}) is smaller than the output power from quantum diode B (P_{outB}). This is because the quantum-confined Stark effect shifts the absorption edge of quantum diode A to long wavelengths, thereby increasing the optical absorption at 856 nm. When V_c is low (approximately zero voltage) the output power from quantum diode A (P_{outA}) is larger than the output power from quantum diode B (P_{outB}) because the quantum-confined Stark effect now shifts the absorption edge of quantum diode B to long wavelengths. When V_c is approximately $V_0/2$, the output powers from both quantum-well diodes are equal. It should be noted that when $V_c \leq 8$ V, the exciton peak will not be shifted to a wavelength longer than 856 nm. If it were, the feedback would become positive, and the absorption would decrease with increasing voltage across the diode.[6]

When we look at the individual output power curves in Fig. 3, we see that they are not linear with drive current over the operating range (in this case ±400 nA), because the absorption does not change linearly with voltage. However, the difference between theses two curves is linear, as shown in Fig. 4. This family of curves represents the difference between the output powers ($D_{out} = P_{outB} - P_{outA}$) from the two quantum-well diodes A and B as function of drive current I_c for different power levels shining on the quantum-well diodes. The difference between the output powers, D_{out}, is linearly proportional to the drive current over a range of more than 4 orders of magnitude of optical power, from 50 nW to 2.5 mW. If the quantum-well diodes were uniformly illuminated, these powers would correspond to intensities of 3.3 mW/cm^2 to 200 W/cm^2, although in our experiment we used small spots (~10-μm diameter), corresponding to intensities as high as 3 kW/cm^2. The limits of the linear range arise when the drive current equals the maximum photocurrent that can be generated by one quantum-well diode, which occurs at maximum reverse bias and maximum absorption (the current in the other diode will thus be zero, or slightly negative, since it will be near the forward-bias condition). By increasing the incident power on the quantum-well diodes, we increase the amount of photocurrent that can be generated, thus increasing the linear range possible. However, the slope remains the same because it depends only on the photon energy. By assuming that each photon absorbed in the quantum well generates one electron of current, we find that the slope should be equal to $h\nu/e$, where h is a constant, ν is the light frequency, and e is the electron charge. The slope of the experimental curves is 1.48 V, which is close to the theoretical value $h\nu/e = 1.45$ V.

To make the optical drive to replace the electrical current source, we actually used two other quantum-

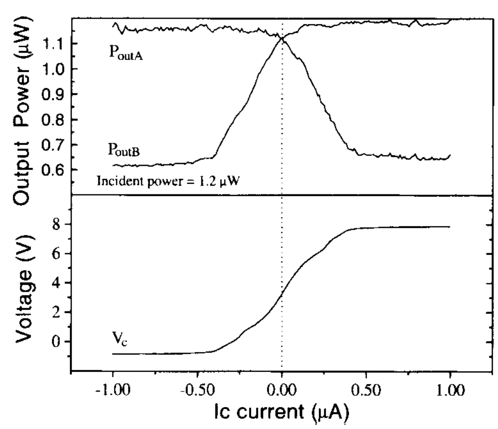

Fig. 3. Output power from the quantum-well diodes and the voltage applied to them as a function of the drive current. The operating wavelength is 856 nm.

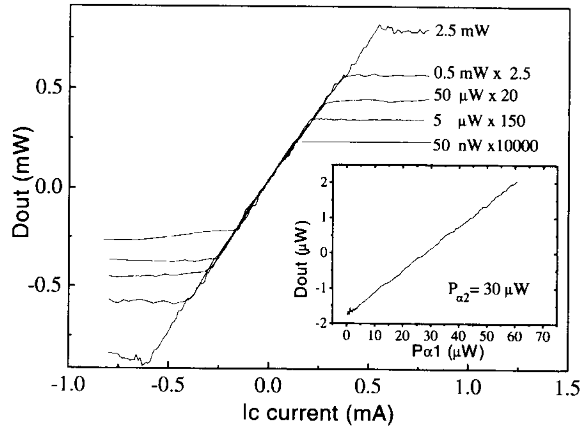

Fig. 4. Difference between the output from the two quantum-well diodes as a function of the source current flowing into the center point for various powers incident on the quantum-well diode. The operating wavelength is 856 nm. For the lower powers, the scales on both axes are modified by the factor shown. The inset shows operation with the optical drive shown in Fig. 2.

well diodes illuminated at a short wavelength of ~780 nm, whereby their responsivity was essentially independent of the reverse-bias voltage, such as in a conventional photodiode. The inset of Fig. 4 shows the curve of D_{out} as a function of the incident input power $P_{\alpha 1}$ on the conventional diode 1. We maintained a constant input power ($P_{\alpha 2}$) shining on the other conventional diode, 2. The difference between the output beams is linearly proportional to the difference ($P_{\alpha 1} - P_{\alpha 2}$) between the input beams shining on conventional diodes 1 and 2. It is worth noting that if we assume the same quantum efficiency in both quantum-well and conventional diodes, then D_{out} should be equal to the difference between the incident input powers ($P_{\alpha 1} - P_{\alpha 2}$) (following from the current conservation principle). However, in the present case, D_{out} is smaller than the difference between the incident input powers, because the quantum efficiency of the diodes at 780 nm is low owing to absorption in the top p^+ layer.

It is easy to see how such a circuit can be used to perform image subtraction and spatial derivatives of images. For example, if the input diodes are adjacent photodiodes of equal area, separated by a distance Δx, the current I_c will be proportional to the spatial derivative of the image shining on them. Other spatial layouts of the diodes will give other derivative functions.[1,2] The use of pairs of output beams allows us to represent the positive or negative result of this differentiation and to pass it on to subsequent stages. It is also easy to see that such a circuit can handle differential pairs of light beams at the input by shining the pairs of beams onto the input pairs of diodes. Hence this circuit can be used for multistage bipolar analog processing.

In conclusion, we have demonstrated the concept of the self-linearized differential modulator, we have shown linearity over more than 4 orders of magnitude, and we have shown that a circuit can be driven both electrically and optically, directly demonstrating the ability to subtract two optical powers. It should now be possible to construct two-dimensional arrays of devices for a variety of bipolar analog optical processing applications.

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*Permanent address, Department of Physics, University of Florence, L. go Enrico Fermi 2, 50125 Florence, Italy.

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