Self-linearized analog differential self-electro-optic-effect device

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We describe, demonstrate, and characterize an analog self-electro-optic-effect device that gives a difference between two optical output powers that is linearly proportional to an electrical or an optical drive. Such a device should permit bipolar (positive and negative) processing in novel image processing arrays. The device is able to operate over a range of more than 4 orders of magnitude of optical power from 50 nW to 2.5 mW, corresponding to uniform incident intensities as low as 3.3 mW/cm^2. The frequency response (3-dB limit) varies linearly from 7 kHz at 1-μW absorber power to 3.5 MHz at 1 mW of absorbed powers.

Introduction

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 to give devices of many different possible functions[1,2] associated with an electrical circuit. In the simplest SEED's, the photocurrent generated by absorbed photons in a reversed-bias diode influences the voltage across the diode by passing through an appropriate electronic circuit. The voltage across the diode influences the absorption of light by the diode and therefore the photocurrent, hence establishing a feedback. The behavior of such SEED's depends on the electronic circuit configuration and the sign of the feedback. If the feedback is positive, the circuit can be operated in a bistable or an oscillation mode; if the feedback is negative the circuit can operate as a self-linearized modulator, a light-by-light modulator, or an optical level shifter.[3] Usually such SEED's have been operated in a positive feedback mode in digital applications.[1,2] Here, however, we explore novel analog features that operate in a negative feedback mode.[4] In particular, we demonstrate and characterize modes using two light beams and two diodes that permit linear, bipolar optical-processing functions. Some of this work has been briefly reported by us before.[5] Here we give an extended discussion including especially the frequency response on the device and the dependence of device operation on various parameters.

To understand how the SEED can operate as an analog device we show in Fig. 1 the absorption of the quantum-well diode as a function of wavelength for three reverse-bias voltages applied to it (0, 8, and 12.5 V). When the voltage is increased across the quantum well, the quantum-confined Stark effect[6] shifts the whole band gap, including the exciton absorption peak, to a longer wavelength. We analyze the circuit behavior for two different wavelengths, 850 nm (resonant with zero-bias exciton), and 856 nm (just below the band gap). At 850 nm, the circuit operates in the positive feedback mode because the initial absorption at zero bias (solid curve) decreases with increasing voltage, as shown by the curves at 8 V (dashed curve) and 12.5 V (dotted curve). At a wavelength of 856 nm, the circuit operates (at least initially) in the negative feedback mode because the initial absorption at zero bias (solid curve) increases with increasing voltage. In this case, the maximum voltage at which the absorption keeps increasing is approximately 8 V (dashed curve), as indicated by the arrow at 856 nm. If we increase the voltage further, the exciton peak shifts beyond the wavelength of operation, and the absorption starts to decrease (dotted curve), resulting in a bistable operation again. [However, choosing a sufficiently low supply voltage (i.e., $V \leq 8$ V) can prevent this bistable operation at 856 nm.] It is easy to see that the operation mode of the device can be changed by tuning the wavelength of operation.

In this work we demonstrate a new mode of operation for SEED's using their analog negative

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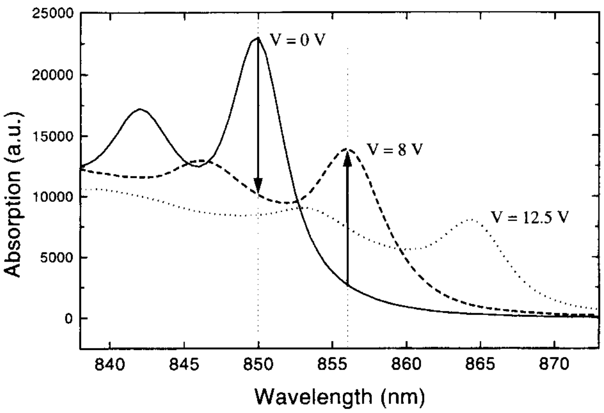

Fig. 1. Absorption of the quantum well as a function of wavelength for 0 V (solid curve), 8 V (dashed curve), and 12.5 V (dotted curve) voltages applied to it. The shift to a long wavelength is due to the quantum-confined Stark effect. The absorption at the wavelength of 850 nm decreases with increasing voltage, but for 856 nm the absorption increases as required for analog applications.

feedback features. This device was recently proposed as a new analog SEED circuit operating with differential pairs of light beams.[4] The key to this device is the use of a negative feedback self-linearized mode of simple SEED circuits,[3] extended here to a novel circuit with two quantum-well modulator–detector diodes in series. 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 differential circuit overcomes this problem and permits many different analog functions to be performed, including addition, subtraction, and differentiation of images, correlation, and optically controlled bipolar matrix–vector multiplication.[4] 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, because it was fabricated by the use of the symmetric SEED array process,[7] it is compatible with large, two-dimensional array fabrication techniques.

Experimental Details

The analog SEED structure uses heterostructure layers of 100 Å GaAs wells with 35-Å barriers of $Al_{0.3}Ga_{0.7}As$ grown by molecular beam epitaxy. This 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, which increases the output beam contrast. Each quantum-well diode has approximately a 50 μm × 30 μm area and an antireflection coating to avoid Fabry–Perot effects. The fabrication steps and the layer structure are detailed in Ref. 7.

A Ti:sapphire continuous-wave laser pumped by an Ar laser was used as the source of beams incident upon the quantum-well diodes. In addition we used two Hitachi diode lasers operating at approximately 780 nm as short-wavelength signal input beams. In the frequency-response experiment, the power from the diode laser was modulated by varying the injected current. The output of the quantum-well diodes was measured with Si photodiodes, and the powers were measured with a Coherent power meter. The wavelength of 856 nm, which is longer than the exciton peak wavelength (850 nm) at zero bias, was mostly used for the incident power-supply beams on the quantum-well modulators.

Principle of Operation

Consider a SEED operating in a negative feedback mode, i.e., its absorption increases with increasing voltage. When the illuminated quantum-well diode is driven 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 was not generating enough photocurrent, the net current would charge up the diode, increasing its absorption and hence its photocurrent (for more details on the self-linearized principle, see Ref. 3). Since these diodes create one electron of current for every photon absorbed, the absorbed power is linearly proportional to the drive current:

$$I_c = (e/h\nu)P_{abs}, \qquad (1)$$

where I_c is the drive current, $h\nu$ is the photon energy, and e is the electronic charge. P_{abs} is the absorbed power, which is equal to the difference between the incident and the reflected powers.

The circuit shown in Fig. 2 uses a pair of quantum-well diodes (A and B) that are reverse biased electrically in series and with an electrically generated current I_c injected into the center point between the diodes. (This class of circuit is discussed in greater detail in Ref. 4, but we repeat the key results here for clarity). In this case, applying the above self-

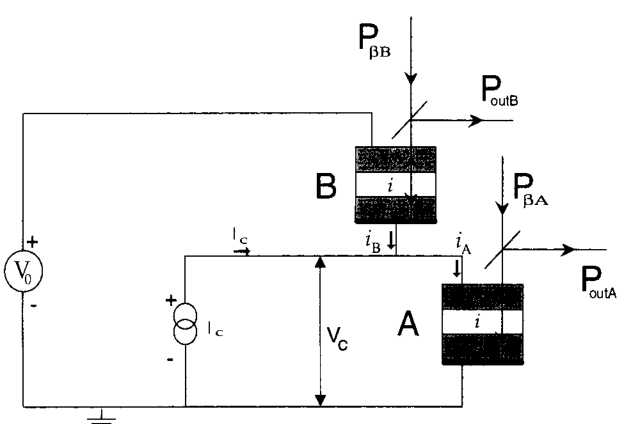

Fig. 2. Self-linearized differential modulator circuits with an electrical current source.

linearizing principle together with conservation of current ($I_c = i_A - i_B$), we can deduce that the difference between the absorbed power in the two quantum-well diodes is linearly proportional to the drive current I_c injected into the center point between them:

$$I_c = (e/h\nu)(P_{absA} - P_{absB}), \quad (2)$$

where P_{absA} and P_{absB} are the absorbed power in quantum diodes A and B, respectively. It is useful to express the operation of the circuit in term of differences between beams. Defining the difference between the incident powers as

$$D_\beta = P_{\beta B} - P_{\beta A}, \quad (3)$$

where $P_{\beta A}$ and $P_{\beta B}$ are the incident powers on quantum-well diodes A and B, respectively, and defining the difference between the outputs from quantum-well diodes A and B as

$$D_{out} = P_{outB} - P_{outA}, \quad (4)$$

where P_{outA} and P_{outB} are the output powers from quantum-well diodes A and B, respectively, then, using expressions (1)–(3), we have

$$D_{out} = D_\beta + (h\nu/e)I_c. \quad (5)$$

In the simple case with equal incident-beam powers ($D_\beta = 0$), the difference between optical output powers is linearly proportional to the drive current.

This mechanism also works for an optoelectronic source for I_c with two reverse-biased conventional photodiodes in series, as shown in Fig. 3. By conventional photodiode, we mean here one that gives a photocurrent that is essentially independent of reverse bias. [In the experiment here, we actually use quantum-well diodes for this function, but we illuminate them at a short wavelength (780 nm), where their responsivity is essentially independent of bias.] In this case, the drive current is proportional to the difference between the absorbed powers in the two conventional photodiodes 1 and 2, i.e.,

$$I_c = (e/h\nu)(P_{abs1} - P_{abs2}), \quad (6)$$

where P_{abs1} and P_{abs2} are the absorbed powers in conventional photodiodes 1 and 2, respectively. We can define the difference between the input powers incident upon the conventional photodiode as

$$D_\alpha = P_{\alpha 1} - P_{\alpha 2}, \quad (7)$$

where $P_{\alpha 1}$ and $P_{\alpha 2}$ are the input powers incident upon conventional diodes 1 and 2, respectively. Assuming for the moment that all input light incident upon the conventional diode is absorbed and each absorbed photon gives an electron current, using Eqs. (6) and (7) we can express Eq. (5) in term of the differences, i.e.,

$$D_{out} = D_\alpha + D_\beta. \quad (8)$$

In the simple case with equal incident-beam power ($D_\beta = 0$), the circuit transfers the difference between two optical input beams ($P_{\alpha 1}$ and $P_{\alpha 2}$) linearly to the difference between two output power beams (P_{outA} and P_{outB}). In our actual circuit, when we are using quantum-well diodes as substitutes for conventional diodes, there is absorption in the top layer of the diodes that does not cause photocurrent, so the simple form of Eq. (8) does not apply; D_α should be multiplied by a factor of less than 1 to account for this, but the linearity of the relation still holds.

Circuit Performance

We characterized the performance of this circuit using both current generators described in Figs. 2 and 3. For simplicity, we use equal powers incident upon quantum-well diodes A and B ($D_\beta = 0$), which results in zero offset, as can be seen from expressions (5) and (8).

A. Electrical Current Generator

Figure 4 shows the individual output powers P_{outA} and P_{outB} from this circuit and the voltage V_c at the

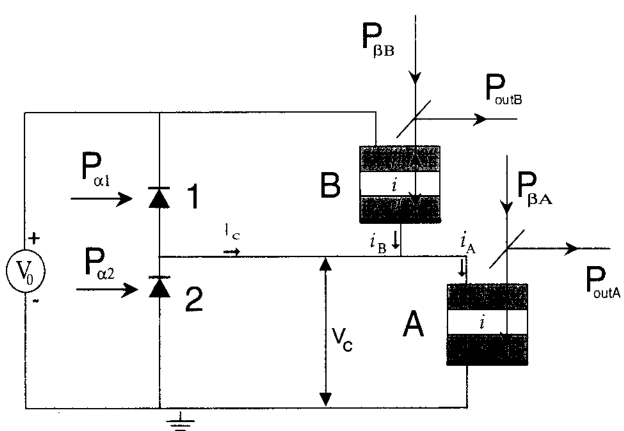

Fig. 3. Self-linearized differential modulator circuits with two conventional photodiodes providing a current proportional to the difference between input powers ($P_{\alpha 1} - P_{\alpha 2}$).

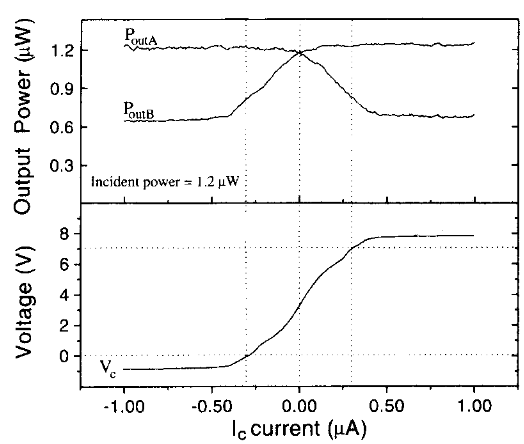

Fig. 4. Output power from the quantum-well diodes and voltage applied to them as a function of the drive current. The operating wavelength is 856 nm.

center point between the two quantum-well diodes as functions of the drive current I_c. When the drive current I_c is scanned from -1 μA to 1 μA, the voltage V_c changes from approximately 0 up to 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. 2 or Fig. 3). 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 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, increasing the optical absorption at 856 nm. When V_c is low (approximately 0 voltage) the output power from quantum diode A (P_{outA}) is larger than 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 approximately equal. It should be noted that $V_c \leq 8$ V will not shift the exciton peak to a wavelength longer than 856 nm. If it did, the feedback would become positive, and the absorption would decrease with increasing voltage across the diode.

When we look at the individual output power curves in Fig. 4, they are not linear with the drive current over the operating range (in this case ±400 nA) because the absorption does not change linearly with voltage. However, the difference between these two curves is linear, as shown in Fig. 5. 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 a function of the drive current I_c for different power levels incident upon 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 incident power in each quantum-well diode (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 curves taken at the lower incident optical powers were multiplied by respective factors on both axes to plot them on the same scale for comparison. D_{out} is 0 when $I_c = 0$ or $V_c \sim V_0/2$ [see expression (5) with $D_\beta = 0$] and positive or negative for $V_c > V_0/2$ or $V_c < V_0/2$, respectively.

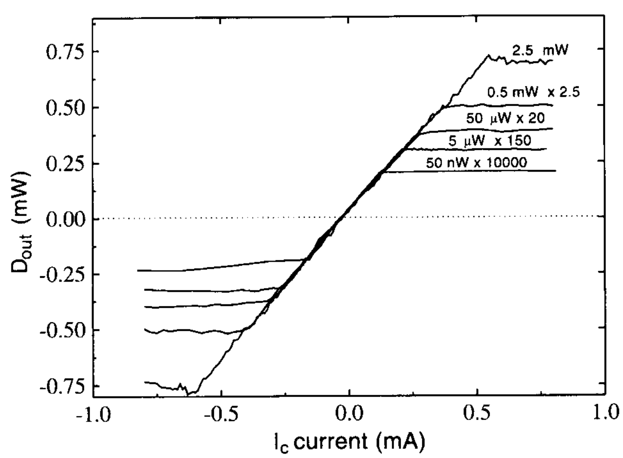

Fig. 5. Difference between the output from the two quantum-well diodes as a function of the source current flowing into the center point for various powers incident upon the quantum-well diode. The operating wavelength is 856 nm. For the lower powers, the scales on both axes are modified by the factor shown.

The 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 (hence the current in the other diode will be zero or slightly negative as it will be near the forward-bias condition). Increasing the incident power on the quantum-well diodes increases the amount of photocurrent that can be generated and so increases the linear range possible (see Fig. 5). The range of linearity can also be extended by increasing the power supply voltage V_0 as this increases the maximum absorption possible in the diodes; this increase in maximum absorption at 856 nm at voltages up to 8 V is clear in Fig. 1 and results from the quantum-confined Stark effect of the exciton on longer wavelengths. In Fig. 6 we show the differential output power D_{out} versus injected current I_c for several voltages V_0, applied on the device. Larger V_0 (up to 8 V) gives a larger linear range in D_{out} against I_c. The optical power incident upon the quantum well and the wavelength (856 nm) were kept constant in this measurement. If we increase the voltage V_0 further (i.e., significantly past 8 V), the absorption starts to decrease (see Fig. 1) and the SEED operates with positive feedback. Note in the 9-V curve in Fig. 6 that the dip after the knee in both extremities in the end of the linear range represents a change to a bistable mode of operation.

Looking at expressions (5) and (8), we see that the slope of D_{out} depends on only the photon energy. In

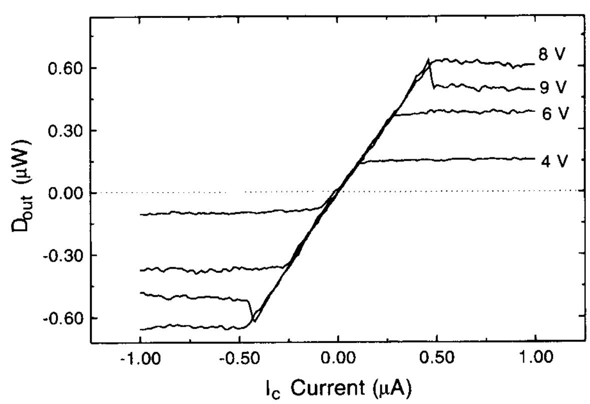

Fig. 6. Difference between the outputs from the two quantum-well diodes as a function of the injected current into the center point for different supply voltages (4, 6, 8, and 9 V) applied on the quantum-well diode. The operating wavelength is 856 nm.

Fig. 7 we show D_{out} as a function of the injected current for two different wavelengths, 854 nm (solid curve) and 856 nm (dashed curve). The supply voltage V_0 and the power incident upon the quantum-well diodes were kept constant. Assuming that each photon absorbed in the quantum well generates one electron of current, the slopes in Figs. 5, 6, and 7 should be equal to $h\nu/e$, where h is Planck's constant, ν is the light frequency, and e is the electron charge. The two experimental curves in Fig. 7 taken at different input wavelengths do indeed show different slopes as expected, with reasonable agreement between the measured slopes of approximately 1.43 V (solid curve) and 1.41 V (dashed curve), and the theoretical values of approximately 1.45 V ($\lambda = 854$ nm) and 1.44 V ($\lambda = 856$ nm). The absolute measured value of the slopes are affected by the absolute accuracy with which optical power can be measured, but the trend of decreasing slope with decreasing photon energy is clear from the results in Fig. 7.

B. Optical Current Generator

In the case of a photodiode current generator in Fig. 3, 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 the reverse-bias voltage and therefore is proportional to the difference between the absorbed powers in these two conventional photodiodes. 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; if it is negative, the current flows in to the center point. If both conventional photodiodes absorb the same amount of incident power, no current will flow; $I_c = 0$. If it is assumed that the conventional diodes create one electron of current for every incident photon, the difference between the absorbed powers in the two conventional diodes is linearly proportional to the difference between the absorbed powers in the two quantum-well diodes with equal incident powers ($D_\beta = 0$), as can be seen from Eq. (7).

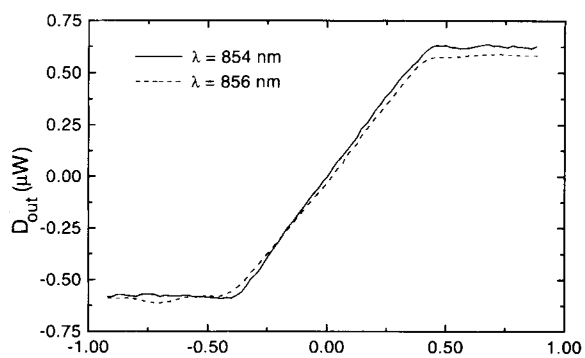

Fig. 7. Difference between the outputs from the two quantum-well diodes as a function of the current injected into the center point for two different wavelengths, 854 and 856 nm, incident upon the quantum-well diode.

As mentioned above, to make the optical drive, for convenience we actually used two quantum-well diodes as the conventional diodes by illuminating them at a short wavelength, ~780 nm, where their responsitivity is essentially independent of the reverse-bias voltage. The curve of D_{out} as a function of $P_{\alpha 1}$, the input power incident upon conventional diode 1, is shown in Fig. 8. In this measurement for each curve, we kept the input power $P_{\alpha 2}$ constant and scanned the input power $P_{\alpha 1}$. As expected, D_{out} is linearly proportional to $P_{\alpha 1}$ and therefore to D_α, the difference between the input powers incident upon conventional diodes 1 and 2, as shown by expression (7). When the input power $P_{\alpha 2}$ is increased from 25 μW (solid curve) to 38 μW, the D_{out} curve shifts to the right (dashed curve). Note that the slope and the range of linearity are still the same. By changing $P_{\alpha 2}$ we shifted the position at which D_α equals zero; this shows that the absolute values of the input powers incident upon the conventional photodiodes are not important; only their difference is. It is worth noting that, assuming the same quantum efficiency in both quantum-well and conventional diodes, D_{out} should be equal to the difference between the incident input powers D_α. 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 as a result of absorption in the top p^+ layer.

Frequency Response

Usually SEED circuits can operate over many orders of magnitude in speed and power (as shown above). Higher speed is obtained by operating at higher power. The upper physical limits on speed are due to absorption saturation and finite carrier sweep-out time.[8] The lowest speed is limited by the leakage current of the device. The present analog differential circuit can be analyzed[4] by the use of a simple linearized model in which the device (Figs. 1 and 2) is represented by a current source in parallel with a capacitor. Operating in a range where the absorp-

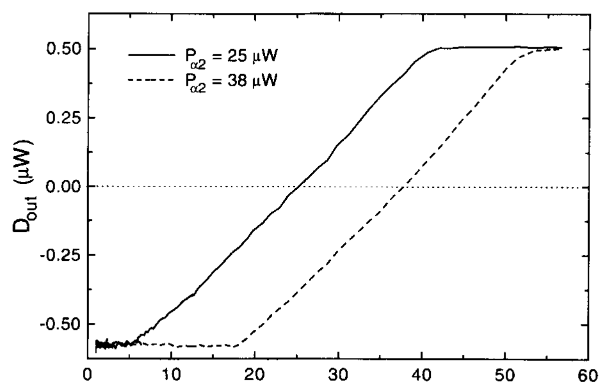

Fig. 8. Difference between the outputs from the two quantum-well diodes as a function of $P_{\alpha 1}$ for two values of $P_{\alpha 2}$: 25 μW (solid curve), 38 μW (dashed curve). The voltage applied on the quantum-well diode and the wavelength operation were 7 V and 856 nm, respectively.

tion A in the quantum well changes approximately linearly with the voltage, for a small perturbation the circuit frequency response is given by

$$f = e\gamma P_{in}/2\pi h\nu C, \qquad (9)$$

where e is the electronic change, $\gamma = dA/dV$ 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.

In this measurement we use four beams incident upon the circuit described in Fig. 2. We kept a constant power incident upon quantum-well diodes A and B. Also we kept constant the incident input power on conventional diode 1. The power incident upon conventional diode 2 was modulated by controlling the current injected on the laser diode. We applied a dc current on the laser with a small sinusoidal modulation, approximately 10%. The modulated signal from the quantum-well diodes was measured with a photodiode and high-frequency lock-in amplifiers.

Figure 9 shows the normalized differential output power amplitude D_{out} as a function of the modulation frequency applied to the input power incident upon conventional diode 1 for several optical power levels incident upon quantum-well diodes A and B. We used equal power incident upon the quantum-well diodes ($D_\beta = 0$). The measured frequency response of the circuit (at 3 dB) for 2 μW (open circles), 20 μW (open boxes), 200 μW (filled circles), and 2 mW (filled boxes) of optical powers incident upon each quantum-well diode was approximately 6.5 kHz, 50 kHz, 600 kHz, and 3.5 MHz, respectively. The performance of the circuit is in reasonable agreement with our model. Using these power levels (considering 50% of absorption; see Fig. 4), a measured capacitance of 1.1 pF, a measured factor γ of 0.06 V^{-1}, and an operating

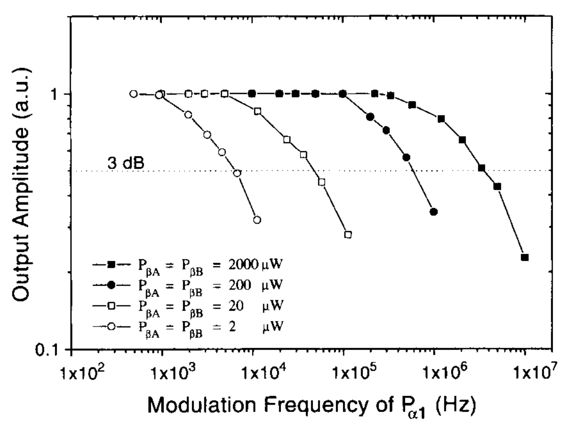

Fig. 9. Modulated amplitude of the difference of the output beam powers from the two quantum-well diodes as a function of modulation frequency of $P_{\alpha 2}$. The voltage applied on the quantum-well diode and the wavelength were 7 V and 856 nm, respectively.

wavelength at 856 nm, we calculated a 3-dB frequency response of approximately 6 kHz, 60 kHz, 600 kHz, and 6 MHz, respectively. As expected, the frequency response of the circuit is linearly proportional to the incident power. We expect that this device could be operated at higher speeds by reducing the capacitance. The device used here was relatively large and had various sources of stray capacitance.

Conclusion

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 the circuit can be driven both electrically and optically, directly demonstrating the ability to subtract two optical powers. We have also measured the frequency response of the device and have shown the dependence of device operation on input power level, supply voltage, and photon energy, in each case comparing the results with the expected behavior. It should now be possible to construct two-dimensional arrays of devices for a variety of bipolar analog optical processing applications.[4]

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