Reprinted from Optics Letters, Vol. 9, page 567, December 1984

Optical-level shifter and self-linearized optical modulator using a quantum-well self-electro-optic effect device

D. A. B. Miller, D. S. Chemla, and T. C. Damen

AT&T Bell Laboratories, Holmdel, New Jersey 07733

T. H. Wood and C. A. Burrus

AT&T Bell Laboratories, Crawford Hill, New Jersey 07733

A. C. Gossard and W. Wiegmann

AT&T Bell Laboratories, Murray Hill, New Jersey 07974

Received July 23, 1984; accepted September 11, 1984

We demonstrate an optical-level shifter and a modulator whose transmission varies linearly with drive current, both based on a new, negative-feedback mode of operation of the recently discovered quantum-well self-electro-optic effect device. The system is compatible with both laser diodes and low-power semiconductor electronics and is applicable in both analog and digital optical processing. An extension of the system gives inverted, linear modulation of a coherent beam by an incoherent light source.

For flexible optical switching and signal-processing systems a variety of active devices, such as switches and modulators, is required. Multiple-quantum-well (MQW) material made of alternate thin (~10-nm) layers of GaAs and GaAlAs has recently attracted attention for potential applications in optical processing. It shows large nonlinear optical effects associated with saturation of its remarkable room-temperature exciton resonances[1] and also large electroabsorptive effects near its band-gap energy.[2–4] These properties are compatible with laser diodes[1] in wavelengths, power levels, and materials. The novel electroabsorptive effect that is due to fields perpendicular to the MQW layers is exceptionally large, permitting the fabrication of high-speed optical modulators of micrometer dimensions[3] with drive voltages and powers compatible with semiconductor electronics. Recently, a new type of optoelectronic device [the self-electro-optic effect device (SEED)] was demonstrated by using this effect.[4] It relies on modulation and detection within the same device, and one possible mode of operation gives optical bistability[4] at low powers.

In this Letter we discuss a different mode of operation of the SEED that yields linearized optical modulation and optical-level shifting; both of these novel functions result from the internal optoelectronic feedback in the SEED. The principle of the SEED[4] is that optical absorption creates photocurrent, which, through an electronic circuit, changes the voltage across the MQW modulator and hence changes the photocurrent, establishing feedback. With the MQW inside a P-I-N diode, the same MQW operates simultaneously as modulator and detector. In the case of optical bistability,[4] the feedback is positive. In the present case, because we operate at photon energies below the absorption edge where absorption increases with increasing reverse-bias voltage (see, for example, Fig. 2 of Ref. 3), the feedback is negative.

The idealized circuit of the device is shown in Fig. 1(a). A current source of current I_c drives the P-I-N diode in reverse bias while a light beam shines through the diode. We find in practice that the internal quantum efficiency of the diode as a detector is close to unity for reverse bias greater than 2 V, so that in this regime the photocurrent is proportional to absorbed power with a coefficient of $e/\hbar\omega$ (where e is the electronic charge and $\hbar\omega$ is the photon energy). The P-I-N diode can also be considered a current source (the photocurrent I_p) in parallel with the internal capacitance of the diode. If the set current I_c exceeds the photocurrent I_p, then the capacitor (i.e., the P-I-N) will charge up as a result of the difference current $I_c - I_p$. However, this increased voltage gives increased absorption and hence increased photocurrent. Therefore the voltage across the diode will increase until $I_c = I_p$. It is easily seen conversely that, if the photocurrent exceeds the set current I_c, the voltage across the diode will decrease to set $I_c = I_p$ again. Hence the point $I_p = I_c$ is a point of stable equilibrium, and the device adjusts itself so that it *absorbs* optical power $P_A = \hbar\omega I_c/e$. Hence the device is a self-linearized modulator with absorbed power linearly proportional to set current I_c. This linearity results from the feedback and requires only constant quantum efficiency of detection. (The modulator transmission with drive voltage is far from linear).[3]

For these experiments we use a sample containing fifty 9.5-nm GaAs quantum wells separated by 9.8-nm $Ga_{0.32}Al_{0.68}As$ barrier layers, all undoped, contained in

0146-9592/84/120567-03$2.00/00

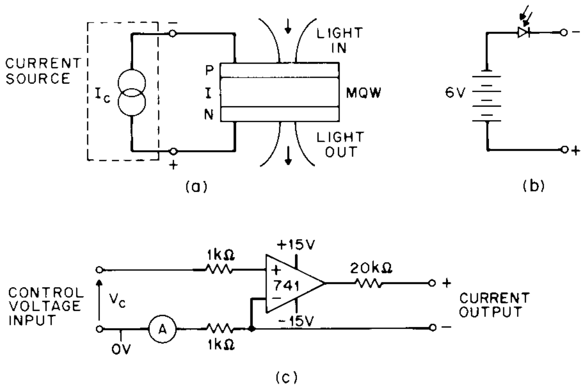

Fig. 1. (a) Idealized schematic diagram showing a current source of current I_c connected to reverse bias the P-I-N diode containing the MQW material in its intrinsic region. The light to be controlled is shone through the whole structure. (b) A simple current source using a reverse-biased silicon photodiode illuminated by a separate lamp. (c) A more ideal current source in which the set current is controlled by a voltage V_c. The amplifier is a standard 741 integrated circuit.

the intrinsic region of a P-I-N diode. The P and N regions consist of $Ga_{0.32}Al_{0.68}As$ and superlattice material; there are also undoped superlattice buffer regions immediately surrounding the MQW, and all these GaAlAs and superlattice regions are transparent at the wavelengths of interest here. The sample was grown by molecular-beam epitaxy on a GaAs substrate. A 600-μm-diameter mesa was etched through the epitaxial layers, and a hole was etched through the GaAs substrate underneath the mesa (using a selective etch) to permit optical access as the GaAs itself is opaque at these wavelengths. This sample is similar to those used for modulators and is described in greater detail elsewhere.[3]

There are many ways of making constant-current sources; we have used two different types here, a light-controlled source [Fig. 1(b)] and a voltage-controlled source [Fig. 1(c)]. The source in Fig. 1(b) consists of a reverse-biased silicon photodiode (SDC 076 11-11-011). This gives a current practically independent of reverse bias between 1 and 7 V and linearly proportional to the bias light shining on the diode; the bias-light source was a conventional tungsten bulb. The source of Fig. 1(c) is more idealized. By varying its output voltage, the operational amplifier tries to pass a current through the load (not shown) so as to equalize the voltages at the amplifier inputs. As negligible current flows into the inputs, this results in a load current proportional to the control voltage V_c. We were not able to measure any deviation from this proportionality experimentally except when the amplifier was driven into saturation at output voltages near ±15 V. The 20-kΩ series resistor is for protection of the load, and the upper 1-kΩ resistor is optional, serving only to protect the amplifier and provide some bias drift compensation.

The light source used to illuminate the MQW was an LDS 821 cw dye laser (optically pumped with a krypton-ion laser) focused to a ~30-μm spot. Optical powers were measuring using a UDT 161 power meter with a silicon detector head.

Typical output power versus current curves are shown in Fig. 2 for four different optical input powers at one wavelength (855.8 nm). These curves were taken using the circuit of Fig. 1(c) with a slow-voltage ramp input (~20 sec) so that any low-frequency laser noise could be filtered. In each case, the output power is independent of current up to a knee, indicated by the dotted–dashed line; in this region the modulator cannot achieve a low enough absorption for self-linearized operation. (Below ~2-V reverse bias there is little further absorption change, and the responsivity falls off because the depletion region no longer extends through the entire MQW.) The dotted–dashed line marking the border of this region has a slope of ~0.15 A/W, which is the responsivity of the device at this wavelength with ~2-V reverse bias. Above this knee, the self-linearized modulator regime starts with power falling off linearly with slope $\hbar\omega/e$ as the current increases. In the case of the circuit of Fig. 1(c), the absorbed power is also linearly proportional to control voltage V_c. The small fluctuations in the curves are believed to be due to the remaining laser noise. Measurements at longer wavelengths show the self-linearized regime starting at lower currents, as would be expected since the absorption and responsivity are less at longer wavelengths. Self-linearized modulation was observed between 854 m and 864 nm. For curves (a), (b), and (c) of Fig. 2, the minimum output power was limited by the maximum absorption in the modulator. A thicker modulator would give lower minimum output power.

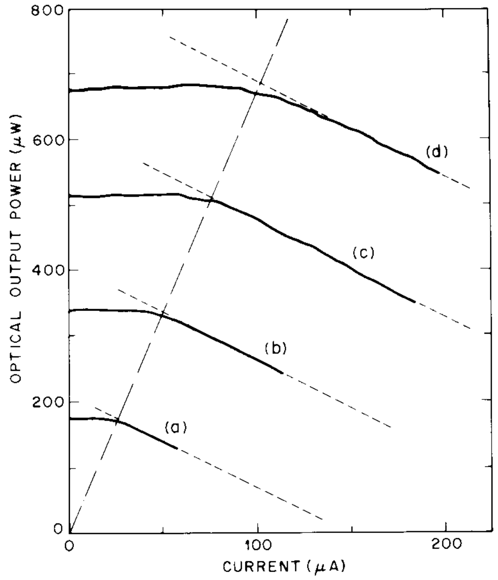

Fig. 2. Optical output power as a function of the current at a wavelength of 855.8 nm ($\hbar\omega$ = 1.449 eV) for four different optical input powers: (a) 330 μW, (b) 650 μW, (c) 980 μW, and (d) 1.30 mW. The dashed lines have slope $\hbar\omega/e$ (as expected for unity internal quantum efficiency). The dotted–dashed line has a slope of 150 mA/W, corresponding to the responsivity of the device near 2-V reverse bias at 855.8 nm.

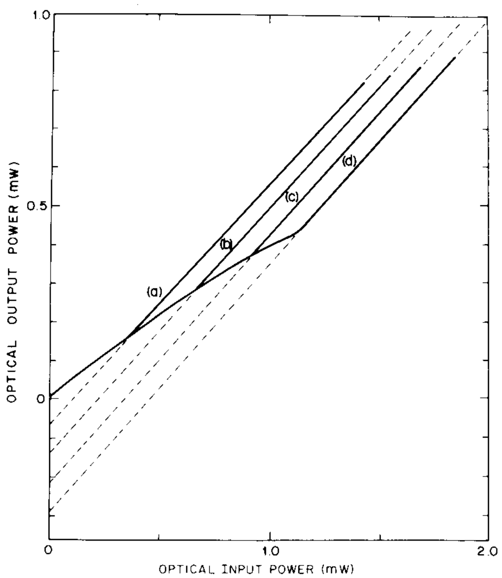

Fig. 3. Optical level shifter action for a SEED under constant current bias of (a) 50 μA, (b) 100 μA, (c) 150 μA, and (d) 200 μA. The operating wavelength is 858.0 nm ($\hbar\omega = 1.445$ eV). The dashed lines are parallel, with intercepts on the output power axis of $-\hbar\omega I_c/e$, where I_c is the appropriate constant-bias current.

We were able to obtain curves similar to those of Fig. 2 by using the current source of Fig. 1(b). In this case the absorbed power was also linearly proportional to the power shining on the silicon diode from the tungsten lamp. In this way we were able to demonstrate a self-linearized, inverting, light-by-light modulator and incoherent-to-coherent modulation converter.

If, instead of holding the optical input power constant and varying the current, we vary the input power under constant current, we obtain the optical input–output characteristics shown in Fig. 3 [again taken using the circuit of Fig. 1(c)]. At low optical input powers, even with the largest voltage available from the current source and consequently the maximum modulator absorption, there is insufficient absorption and/or optical power to generate a photocurrent equal to the set current; consequently the current source outputs its largest possible voltage. However, once the incident power and the maximum absorption are large enough to give a photocurrent greater than the set current of the current source, then the system goes into the self-linearized modulator mode where a constant absorbed power is subtracted from the output power. As the internal quantum efficiency is unity, the input–output characteristic when projected to the output power axis (as shown by the dashed lines) has an intercept of exactly $-\hbar\omega I_c/e$. Thus the level of the optical output signal is shifted by subtraction of a constant baseline. Larger absorption in the modulator would give better contrast between the slopes of the two sections of the characteristic. At higher powers than those shown in Fig. 3, eventually the condition is reached at which the absorption of the modulator cannot decrease further; then the level-shifted curves limit to the maximum transmission possible at the operating wavelength.

In conclusion, we have demonstrated a simple novel optoelectronic device using a quantum-well P-I-N diode in a SEED configuration with negative feedback. We have demonstrated two different classes of operation, one as a linear optical modulator, the other as an optical level shifter, both using current biasing of the SEED. The self-linearized modulator may be useful in analog signal-processing applications for which linearity is crucial. In an extension of the self-linearized modulator using a separate photodiode, the modulation may be controlled by an additional (incoherent) light source to give linear incoherent-to-coherent conversion or linear inversion of optical modulation. The optical level shifter may find applications in analog systems to subtract backgrounds or in optical logic systems to shift or set logic levels at interfaces between devices. An important attribute of these and other[4] SEED devices is their compatibility with diode lasers, light-emitting diodes, and semiconductor electronics, making these devices promising for practical applications.

References

1. See, for example, D. S. Chemla, D. A. B. Miller, P. W. Smith, A. C. Gossard, and W. Wiegmann, IEEE J. Quantum Electron. **QE-20,** 265 (1984).
2. D. S. Chemla, T. C. Damen, D. A. B. Miller, A. C. Gossard, and W. Wiegmann, Appl. Phys. Lett. **42,** 864 (1983).
3. T. H. Wood, C. A. Burrus, D. A. B. Miller, D. S. Chemla, T. C. Damen, A. C. Gossard, and W. Wiegmann, Appl. Phys. Lett. **44,** 16 (1984).
4. D. A. B. Miller, D. S. Chemla, T. C. Damen, A. C. Gossard, W. Wiegmann, T. H. Wood, and C. A. Burrus, Appl. Phys. Lett. **45,** 13 (1984).