Dual-Function Detector–Modulator Smart-Pixel Module

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We describe a smart-pixel circuit that permits the use of a GaAs/AlGaAs multiple quantum well diode to be used both as a detector for data input and a modulator for data output. The module provides the ability to double the number of inputs or outputs to the array and is well suited to cascaded optoelectronic system architectures that require bidirectional communition.

1. Introduction and Background

Surface-normal optical interconnections can be used to provide high-density, high-speed, and global interconnections between electronic components in a high-density VLSI environment. For instance, the field-effect transistor self-electro-optic effect device technology provides the ability to monolithically integrate large-scale-integration GaAs metal-semiconductor field-effect transistor-based electronic circuits with GaAs/AlGaAs multiple quantum well (MQW) detectors–modulators for optical input–output (I/O).[1]

More recently, the ability to attach GaAs MQW light detectors and light modulators onto a prefabricated silicon complementary metal-oxide semiconductor (CMOS) integrated circuit by use of a well-established flip-chip bonding technique has been demonstrated.[2] This permits optoelectronic-VLSI circuits to be readily developed by incorporation into each subcircuit or pixel a detector, a receiver circuit, some local custom-designed processing circuitry, a driver circuit, and a modulator. A potentially large and homogenous array of such pixels, commonly referred to as a photonic smart-pixel array, can thus be fabricated. Two or more smart-pixel arrays can communicate with each other through an optical interconnection system.

Typically, the optical detectors and modulators are identical devices: simple p-i-n diode structures with an active MQW intrinsic region. The same process is used to fabricate both the detectors and the modulators, resulting in a homogenous array of GaAs/AlGaAs MQW modulator–detector devices. The electronic circuitry and the optical interconnection system distinguishes the optical receivers from the optical modulators. In systems that utilize such devices the optical system must provide at least two distinct optical paths to the chip. For photonic-switching applications, this is typically done by use of a beam splitter: One path is used to place the arrayed optical inputs onto the detectors, and another path is used to power the modulators for readout of the arrayed optical outputs. For instance, multichip optical systems have previously been demonstrated by combination of polarization with space-division multiplexing[3] and polarization with pupil-division multiplexing[4] to provide separate optical paths for input data, output data, and modulator readout illumination. This allows smart-pixel chips to be cascaded at the expense of some optical power losses arising from the beam splitters, scattering, etc.

The design described above is well suited for feed-forward systems such as photonic multistage switches but lacks the flexibility to implement additional feedback or recurrent connections without additional optical system losses. For instance, a smart-pixel array fast Fourier transform processor with an associated array optical memory would require connections to (write cycle) and from (read cycle) the optical memory device, which may also be an optoelectronic chip.[5] These connections would be in

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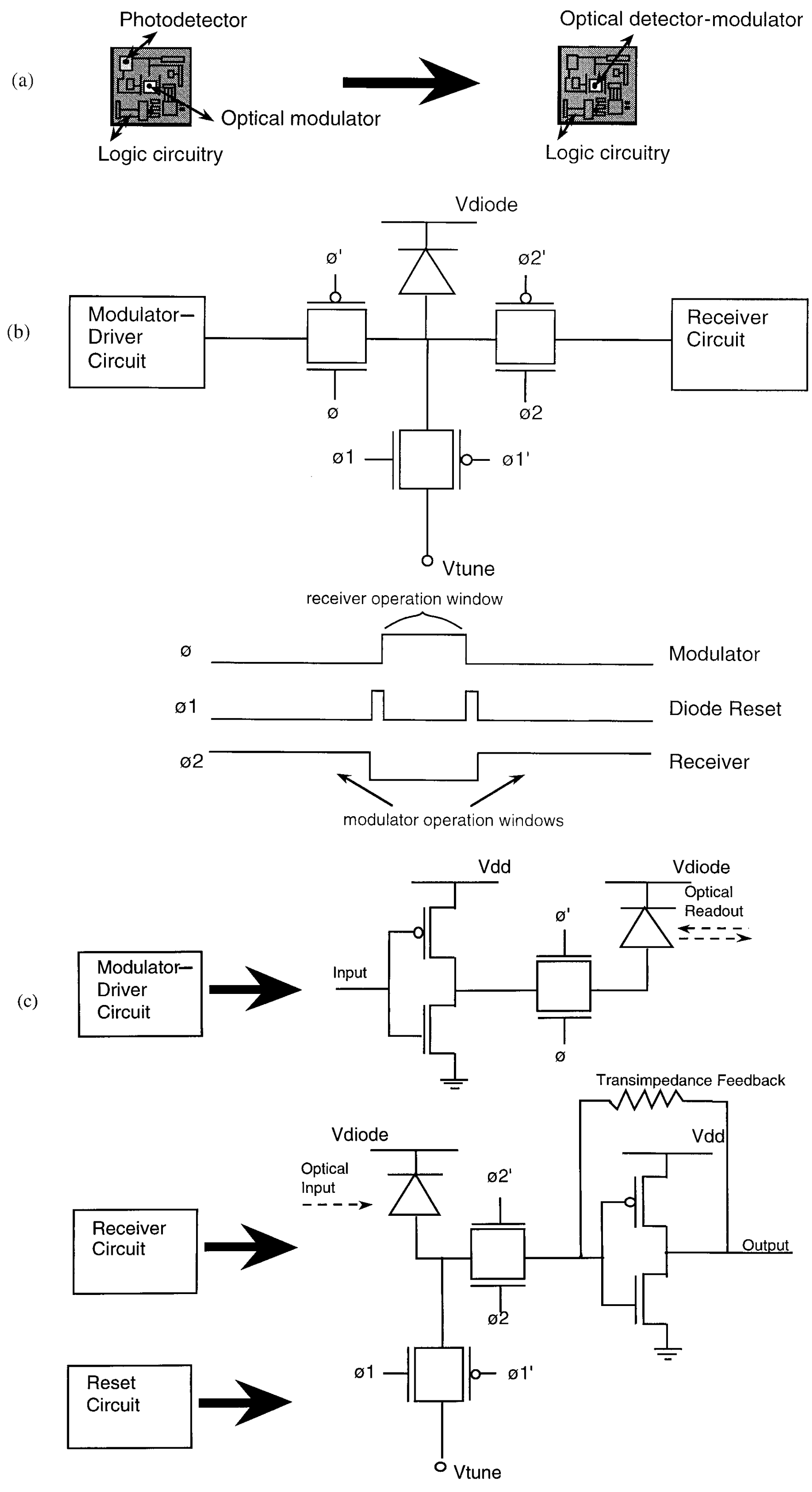

Fig. 1. Schematic diagrams of the dual-function receiver–transmitter circuit: (a) The same diode or diode pair (for two-beam receivers) used for both optical input and output. (b) The control channels Ø and Ø2 are complementary signals. When Ø = 1, the circuit acts as a transmitter; when Ø2 = 1, the circuit behaves as a receiver. The additional pass gate is used to reset the receiver–transmitter (when Ø1 = 1) input to the proper operating potential Vtune between the transmit and receive phases. (c) In the fabricated circuit, a simple inverter buffer was used as the transmitter, and a transimpedance amplifier circuit constituted the receiver front end.

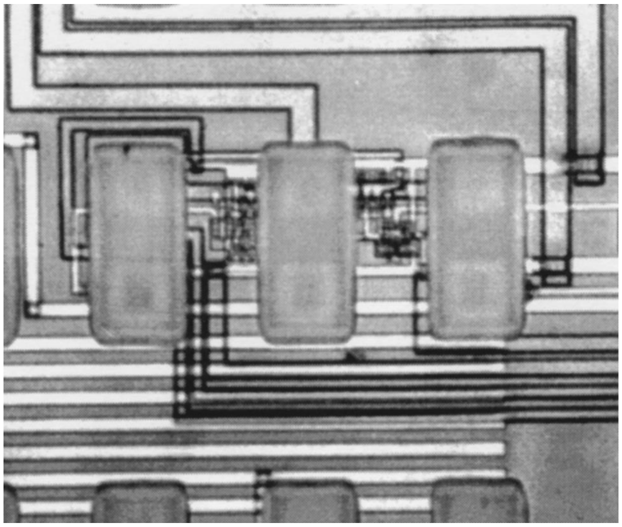

Fig. 2. Microphotograph of the fabricated circuit. The diodes are 20 μm × 50 μm and are situated directly above the circuit.

addition to any other array optical connections to other parts of the system. In fact, several applications in parallel optoelectronic computing, image processing, adaptive optoelectronic neural networks, and switching rely on the ability to perform bidirectional communication between integrated circuits.[5–7]

Optical systems that capitalize on bidirectional communication between smart-pixel arrays for these applications have been investigated.[6,7] If such systems were built with smart pixels that use the same device(s), hence the same optical paths for both input and output, the simplicity and efficiency of the system could be improved.

2. Combination of Receiver and Modulator–Driver Functions

A procedure that would facilitate the implementation of feedback and recurrent connections would be to use the same physical device (i.e., the MQW diode) for both the detector and the modulator circuits. During the receive cycle, the diode would act as a detector and have its output photocurrent directed to the input of an electronic receiver circuit. For single-ended (one-beam) optical communication, this can be accomplished by connection of the output of the p junction of the diode to the input of the receiver circuit. During the transmit cycle, the device would act as a modulator, and have the p junction of the p-i(MQW)-n diode connected to the output of a driver circuit.

Figure 1(a) depicts the circuit concept. A schematic of the circuit for a silicon CMOS implementation is shown in Fig. 1(b). Pass transistors are used to isolate the driver and receiver circuits during the corresponding transmit and detect cycles. An alternative to the use of a pass transistor is the use of a tristate buffer. Two control channels (optical or electrical), Ø and Ø2, are used to switch between the two states according to the system's operating code. An additional pass gate (Ø1) is used to reset the

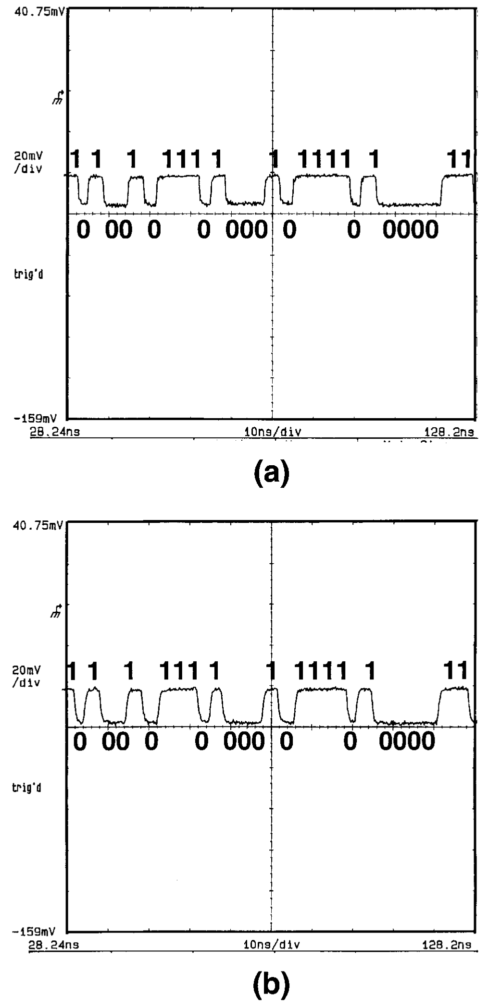

Fig. 3. Operation of the dual-function circuit as (a) a receiver at 300 Mbits/s and (b) a transmitter at 300 Mbits/s. The maximum bit rate of the circuit was measured to be 400 Mbits/s, limited by the receiver bandwidth.

receiver–modulator diode to the proper operating potential to avoid spurious signals; this is done before the circuit is toggled between receiver and modulator–driver modes. In certain situations it may be beneficial to use different operating potentials (Vtune) for the receiver and modulator operation modes. In Fig. 1(b), the high voltage (Vdiode) is assumed to be the same in both operation modes. If this is not the case, then the supply voltage can also be switched between cycles. Figure 1(c) shows one possible implementation of the circuit by use of a well-known transimpedance receiver and a simple single-stage buffer circuit. Figure 1 shows the case for a single-ended system with one diode per optical input. The circuit may also be used for differential optical I/O signals by use of a pair of diodes.

3. Experimental Verification

We have implemented and tested the optoelectronic circuits shown in Fig. 1(c). The transimpedance receiver design used in this implementation was de-

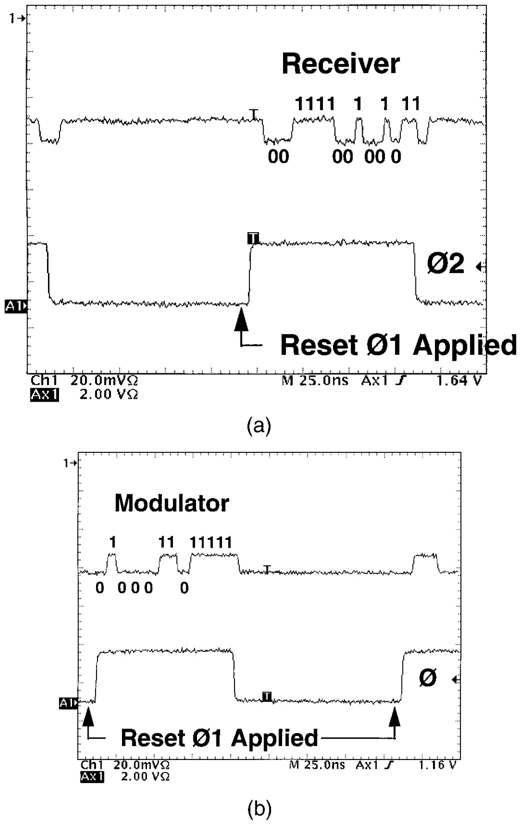

Fig. 4. (a) Receiver operation at 200 Mbit/s with reconfiguration at 5 MHz (top trace). The receiver-enabling signal (Ø2) had a 45% duty cycle (bottom trace). (b) Modulator operation at 200 Mbits/s with reconfiguration at 5 MHz (top trace). The modulator-enabling signal (Ø) had a 45% duty cycle (bottom trace). A short pulse (10% duty cycle) was applied to the reset signal (Ø1) before the transmit and receive cycles.

scribed in greater detail previously.[8] The circuit was implemented in 5-V, 0.8-μm CMOS technology and required an area of approximately 35 μm × 125 μm; two 20-μm flip-chip bonding pads in the topmost (third) layer of metal were used for attachment to the coplanar n contact and p contact of the MQW diode. Figure 2 shows a microphotograph of the fabricated circuit. The static power dissipation of the circuit was 3.5 mW. First the receiver and modulator–driver were individually tested with nonreturn-to-zero data. The receiver subcircuit was operated at 200, 300, and 400 Mbits/s with input photocurrents of 3, 4.5, and 6.5 μA, respectively; these measurements correspond to receiver sensitivities of 60, 60, and 65 fJ, respectively. Figure 3(a) shows the bit pattern obtained from the receiver at 300 Mbits/s. Beyond 400 Mbits/s, degradation in the signal occurred as a result of the receiver bandwidth limits.[8] Figure 3(b) shows the corresponding operation of the modulator subcircuit.

Next, dynamic switching between receiver and modulator functionalities was tested. Figure 4(a) shows a 50% duty-cycle clock signal at 5 MHz applied to control channel Ø and the corresponding trace of the modulator circuit at 200 Mbits/s. Figure 4(b) shows a 40% duty-cycle clock applied to control channel Ø2 and the corresponding receiver output signal at 200 Mbits/s. A short pulse, synchronized with the clock, for the diode-reset voltage was applied at a 5-MHz repetition rate. In this case the power dissipation of the curcuit was measured to be 6 mW. We expect that higher reconfiguration rates (≈100 MHz) will be possible when on-chip generation of the appropriate control signals is implemented.

As mentioned above, the diode-reset voltage and an additional pulse prevent a spurious bit from being injected into the output bit stream of the receiver. The dual-function circuit that was fabricated thus required three off-chip control signals. An alternative method of preventing transmission errors when switching between modulator and receiver functions is to provide one control signal and its inverse to the receiver and modulator–driver circuit, respectively, and to gate the outputs of the receiver and modulator–driver with a second control signal that provides a window where the receiver (or modulator–driver) output is valid. In this case, diode reset can be performed when neither receiver nor modulator output is valid.

Another variation of the circuit involves the use of receivers that do not have to be prebiased, (e.g., an integrating high-impedance receiver). Such a receiver could remove the need for the diode-reset voltage control and the second control signal. Finally, the dual-function circuit could also be used as a receiver and an active transmitter driver. One could accomplish the latter by driving the diode into forward bias, i.e., as a light-emitting diode.

4. Conclusions

One of the benefits of the use of the dual-function detector–modulator smart-pixel module described is that a number of optical I/O's to a smart-pixel array potentially can be doubled since each optical diode can act as both a modulator and a detector. The circuit is particularly advantageous for cascaded optoelectronic chips that multiplex between the transmit and receive modes, as is the case, for instance, in a processor-to-memory interconnect or in a shared-bus-based interconnect between pixels that reside on different chips.

For certain optical system designs the use of the dual-function detector–modulator module can help reduce power losses associated with providing multiple optical paths to the optoelectronic chip. The dual-function module is also useful when coupling optoelectronic devices directly to fibers. Low-cost packaging for coupling surface-normal reflective modulators directly to single-mode fibers has recently been demonstrated.[9] When combined with the dual-function circuit, such a package could be used to provide bidirectional communication for data-networking applications.

In summary, we have designed and implemented a receiver–modulator–driver circuit that allows a diode to be used as a detector or a modulator, depending on a control signal. The control signal can be switched at high speed, allowing the circuit to be reconfigured during system operation. Experimental results confirm receiver and modulator–driver operation up to 400 Mbits/s, with reconfiguration at up to 5 Mbits/s. From the system point of view, the advantages of the circuit include (i) a larger number of parallel optical I/O's to the circuit, (ii) a reduced number of separate optical paths to the circuit, and (iii) simpler coupling of the I/O modules to fibers.

A potential issue for the circuit is the extra capacitive loading of the receiver and modulator circuits by the pass transistor or the tristate buffer connecting the reverse-biased p-i-n diode to the receiver and driver circuits. But this is typically a negligible fraction (a few percent or less) of the total capacitive load. Based on experiments to date, no significant effect on the performance of either the modulator–driver or the receiver circuit (up to 400 Mbits/s) has been observed.

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