Bistable optical electrical/microwave switching using optically coupled monolithically integrated GaAlAs translasers

K. Y. Lau
Ortel Corporation, Alhambra, California 91803
A. Yariv
California Institute of Technology, Pasadena, California 91125

(Received 25 April 1984; accepted for publication 16 July 1984)

A novel switching device consisting of optically coupled laser and field-effect transistor monolithically integrated on a semi-insulating substrate is demonstrated. The physical origin of the bistable behavior is illustrated. The input and output to this device can take the form of optical and/or electrical signals. Applications of this device in optical, electrical, microwave switching, and pulse-position/pulse frequency demodulation are illustrated.

Bistable switching devices occupy a central role in the area of signal processing. Electronic switching devices (electrical in-electrical out), commonly known as Schmidt trigger, have proven themselves to be indispensable in this area of application. Purely optical bistable devices (optical in-optical out) are under consideration for possible applications in future systems.[1] Between the approaches of purely electrical or purely optical switching are hybrid devices with electrical and/or optical inputs and outputs. Examples of these are the recently reported bistable injection laser[2] and hybrid optoelectronic/electro-optic bistable optical devices.[1,3] In this letter, we report on optical, electronic, and microwave switching characteristics of a monolithically integrated optoelectronic bistable device consisting of a laser and a metal-semiconductor field-effect transistor (MESFET) which are connected in series electrically and are optically coupled (hereafter referred to as the optically coupled (OC) "translaser," which was the name given to a general class of device consisting of monolithically integrated lasers and transistors[4]). Bistable switching can be effected with either an electrical or an optical input signal, and the output is available both in an optical and/or electrical form. The laser diode and the FET in this integrated device are capable of very high speed operation up to microwave frequencies (several GHz). These qualifications combined make the device potentially useful in a variety of applications ranging from purely bistable electronic or optical switching, to optical control of microwave signals and demodulation of optical pulse position (PPM)/ pulse frequency modulated (PFM) signals.

A schematic diagram of the basic OC translaser is shown in Fig. 1 and consists of a series-connected buried heterostructure injection laser and a MESFET integrated monolithically on a semi-insulating GaAs substrate. The device configuration is similar to that reported previously,[5] except that the FET channel in the present device is closer to the edge of the mesa (75 μm versus 115 μm as in the previous device) and the embedding GaAlAs layer of the laser is higher in Al content (0.55). These two factors lead to increased optical coupling of the scattered laser light along the optical waveguide into the FET channel. The fabrication process for this devices is similar to that reported previously.[5] The threshold current of the laser diode is $\sim$20 mA which is typical of this laser structure. The FET shows the usual transconductance characteristics as the gate voltage (V_g) is decreased (i.e., made more negative) until the channel abruptly cuts off at $V_g = V_c$, where V_c is typically between -7.5 and -9.5 V, depending on the drain-source bias voltage (V_{ds}). The channel does not recover until V_g is raised substantially above V_c. These bistable characteristics are shown in Fig. 2, where the variation in drain current with applied gate voltage is plotted, for various values of source-drain voltage.

The cause of this bistability as due to coupling of laser emission into the FET channel is positively identified by grounding the drain of the FET (which is also the cathode of the laser) and operating the FET and the laser independently. In this condition, a "normal" transistor characteristic without any bistable behavior is observed regardless of whether the laser is operating or not, except that the pinchoff voltage V_c increases from -8 to -12 V as the laser current is increased from 0 to 10 mA (at which point the laser is emitting 100 mW/facet). Thus, in operating the OC translaser device, an increase in the gate voltage increases the drain current and hence the amount of laser emission, which, due to light absorption in the FET, decreases the

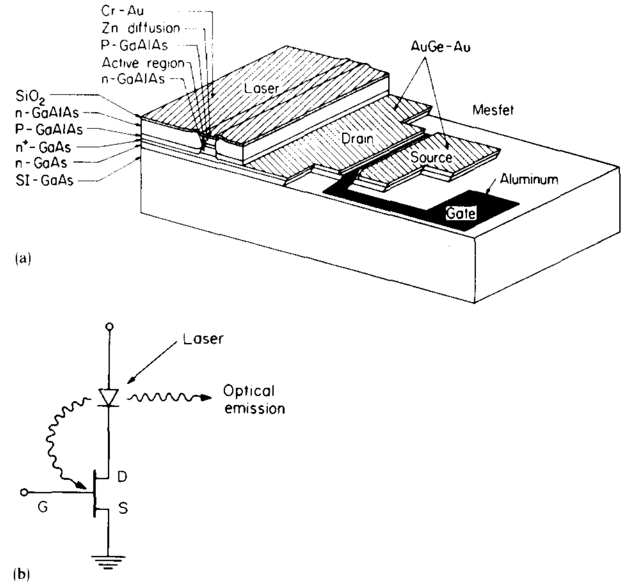

FIG. 1. (a) Schematic diagram of the monolithically integrated OC translaser and (b) equivalent circuit.

0003-6951/84/190719-03$01.00

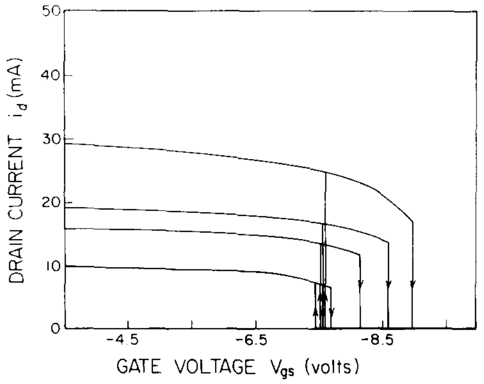

FIG. 2. Bistable drain cuurent-gate voltage characteristics of the OC translaser. The different curves are obtained at various drain-source voltages.

resistance of the gate channel by phototransistor or photoconductive effect,[6,7] and consequently further increasing the drain current. This positive feedback can lead to bistable characteristics as observed in our devices. Since the bistable characteristics originate from optical absorption in the FET, it comes as no surprise that bistable characteristics similar to those of Fig. 2 can be obtained by varying the amount of external illumination on the FET gate.

The basic electrical switching of a OC translaser is shown in Fig. 3. The dc gate voltage V_g is chosen so as to bias the device somewhere near the middle of the hysteresis loop of Fig. 2. Small electrical pulses (top trace) superimposed on the bias gate voltage then switch the drain current on and off. The switching speed is limited intrinsically by the speed of the FET and by the current modulation response of the laser. The MESFET used here is capable of multi-GHz bandwidth and hence the response of the MESFET is well below 50 ps. The laser response time depends on the bias level during switching. In our devices, the laser must switch on from essentially zero current and it is well known that under this condition, the laser will experience a delay time of several nanoseconds before lasing commences, during which the laser acts as an light-emitting diode (LED).[8] However, the optical coupling between the laser and FET in our OC translaser is sufficiently strong that switching can occur with the laser operating below threshold, i.e., in the LED mode. The combined switching response time of the OC translaser is thus limited by the optical response speed of the LED, which is of the order of a few nanoseconds, the spontaneous lifetime of the carriers in GaAs. The measured electrical switching on-off time of the OC translaser is, however, about 100 ns. The fact that this discrepancy in switching speed originated from lumped capacitive elements of the connector and coaxial cables was ascertained when optical switching experiments reveal a switch-on time of ~7 ns. In the optical switching experiment, a separate GaAlAs laser was biased above threshold and modulated by positive and negative current pulses similar to those shown in the top trace of Fig. 3. The laser light was focused onto the gate channel in the OC translaser. Switching behavior similar to that shown in the lower trace of Fig. 3 is obtained by purely optical means. The

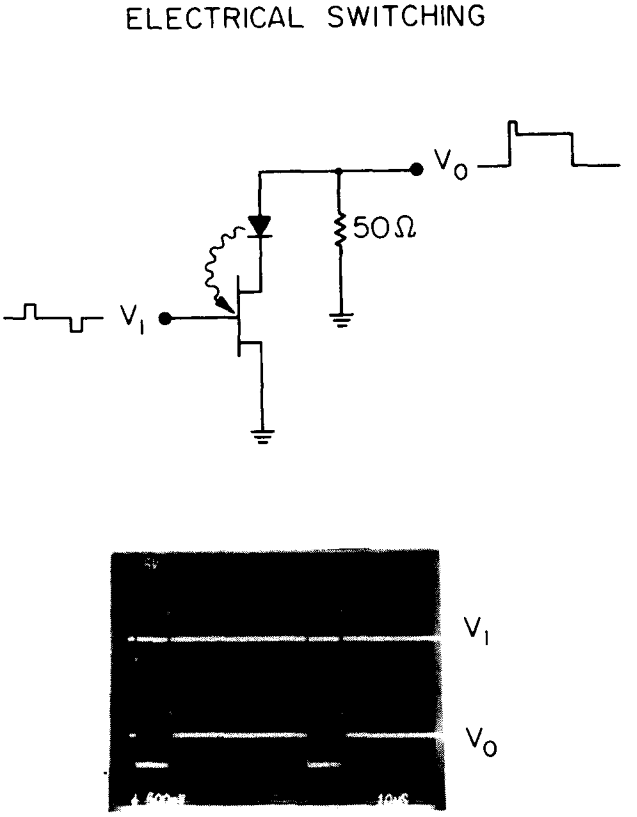

FIG. 3. Electrical switching of the OC translaser, Top trance: input voltage to gate; lower trace: output from the OC translaser.

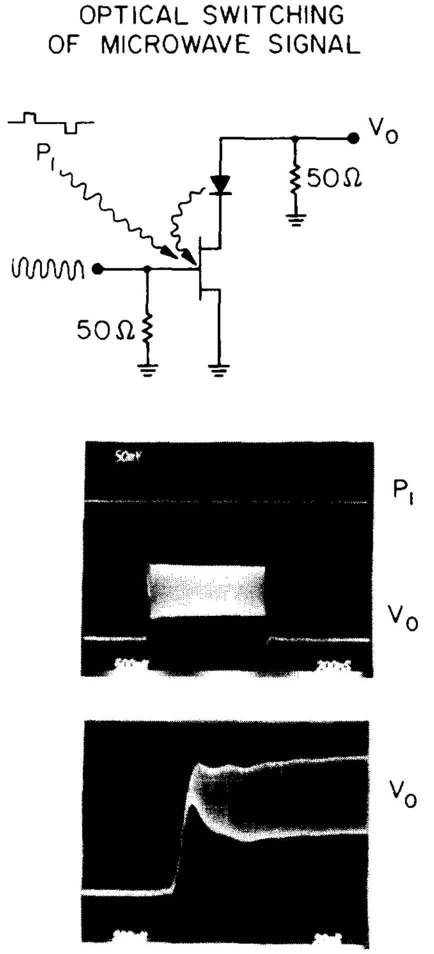

FIG. 4. Optical control of microwave signals. Upper scope picture, upper trace: control optical pulses incident on gate; lower trace: switched microwave output from the OC translaser; lower scope picture, expanded view of switch-on, 20 ns/div.

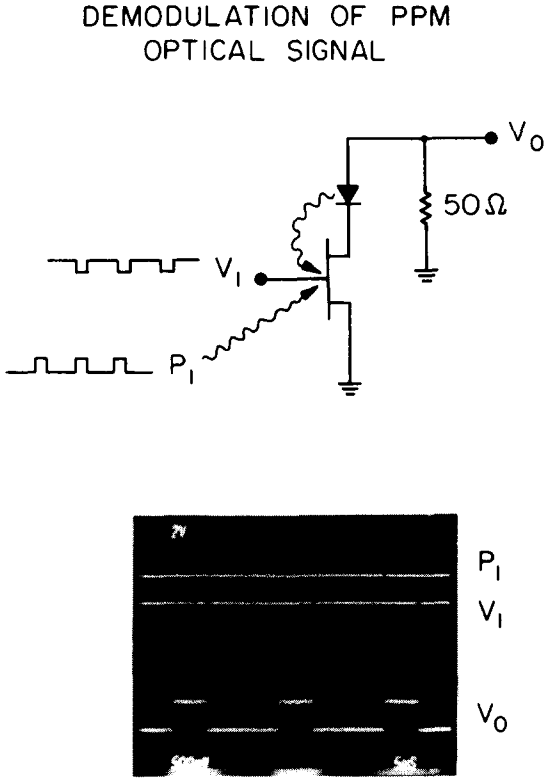

FIG. 5. Use of the OC translaser as an optical PPM demodulator. Top trace: incoming optical pulses incident on gate; middle trace: electrical clock pulses applied to gate; lower trace: output from the OC translaser. Demodulation is accomplished by low-pass filtering the output.

switching time, as mentioned before, was improved to ~ 7 ns. This response time is consistent with that expected from spontaneous recombination lifetime considerations.

One might expect that by reducing the optical coupling between the FET and the laser, the latter can be operated at or above lasing threshold while in the OFF state, and consequently the switching time can be reduced to below 100 ps—the response time of a laser biased above threshold.[9] As it turns out, the exact physical mechanism of optical absorption in the MESFET, whether it be phototransistor or photoconductive effect, has major influence on whether the above mentioned scheme is possible. An analysis[9] shows that if phototransistor effect dominates, the above scheme will work and picosecond switching time will ultimately be attainable in this device, while such will not be the case if photoconductive effect dominates. Further work in this area will show not only the ultimate speed potential of the OC translaser but also sheds light on the exact photoresponse mechanism of MESFET devices.

The OC translaser can be used as a microwave bistable switch. The microwave signal (with frequencies in the range of 0.5–5 GHz) is coupled into the gate of the FET through a capacitor. When the device is in the OFF state, the channel of the FET is cut off, which blocks the input microwave signal from reaching the output port of the device, the isolation being ~ 45 dB. A small positive voltage pulse applied to the FET gate can then turn the device on. This can also be accomplished by illuminating the gate of the FET with optical pulses as described earlier. This is illustrated in Fig. 4, where the top trace in the upper scope picture shows the optical input to the OC translaser and the bottom trace shows the gated microwave signal. The lower scope picture shows an expanded view during switch-on, illustrating a switching time of ~ 7 ns. The microwave signal at the output port in this operating state is attentuated by a factor of $g_m R$, where g_m is the transconductance of the FET and R is the load resistance at the gate, which is typically $50\,\Omega$. The value of g_m is ~ 7 mmho in our device and therefore the loss is 9 dB. This value can be much improved and it is very conceivable that this microwave switch can actually provide gain.

The use of the OC translaser device as an optical PPM demodulator is illustrated in Fig. 5. An incoming pulse position (or pulse repetition rate) modulated optical pulse train is incident on the gate of the FET in the OC translaser. A timing clock signal is applied electrically to the FET gate. The bias voltage at the gate is adjusted so that the device is turned on by the optical pulse and subseqently turned off by the electrical clock pulse. The fraction of the cycle which the OC translaser is in the ON state is proportional to the time deviation of an optical pulse from the clock pulse. The PPM signal can be retrieved by low-pass filtering the output from the OC translaser.

The above experiments demonstrate the versatility and the wide range of applications in which the monolithically integrated OC translaser can be used. As mentioned before, the switching time of the present OC translaser is limited by the spontaneous recombination time of the carriers in the laser diode (i.e., the modulation speed of an LED) since the laser must be switched on from way below threshold. A reduction in the optical coupling between the laser and the FET can conceivably cause the switch-on to occur with the laser already at or slightly above threshold, thus greatly reducing the switch-on time to less than 100 ps. This, however, is contingent upon the response mechanism of the MESFET being due to phototransistor effect.

The authors acknowledge Dr. S. Margalit for useful and enthusiastic discussions. This research is supported by Defence Advanced Research Project Agency and Naval Research Laboratory.

[1] H. M. Gibbs, S. L. McCall, and T. N. C. Venkatesan, Opt. News **5**, 6 (1979), and references therein.
[2] Ch. Harder, K. Y. Lau, and A. Yariv, IEEE J. Quantum Electron. **QE-18**, 1351 (1980).
[3] Y. Ogawa, H. Ito, and H. Inaba, Jpn. J. Appl. Phys. **20**, L646 (1981).
[4] J. Katz, N. Bar-Chaim, P. C. Chen, S. Margalit, I. Ury, M. Yust, and A. Yariv, Appl. Phys. Lett. **37**, 211 (1980).
[5] I. Ury, K. Y. Lau, N. Bar-Chaim, and A. Yariv, Appl. Phys. Lett. **41**, 126 (1982).
[6] J. G. Gammel and J. M. Ballantyne, Digest of IEEE International Electron. Dev. Meet., Washington D. C. 1978, p. 120.
[7] T. Sugeta and Y. Mizushima, Jpn. J. Appl. Phys. Lett. **1**, L27 (1980).
[8] H. Kressel and J. K. Butler, *Semiconductor Lasers and Heterojunction LED's* (Academic, New York, 1975), p. 555.
[9] K. Y. Lau and A. Yariv (unpublished).