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OPTICALLY CONTROLLED MICROWAVE DEVICES AND CIRCUITS:

EMERGING APPLICATIONS IN SPACE COMMUNICATIONS SYSTEMS

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SUMMARY

Optically controlled microwave devices and circuits, either directly illuminated or interfaced by an optical fiber, have the potential to simplify signal distribution networks in high frequency space communications systems. In this paper the optical response of GaAs/GaAlAs HEMT and GaAs MESFET microwave devices is presented when directly illuminated by an optical beam. Monolithic integration of optical and microwave functions on a single gallium arsenide substrate is considered to provide low power, low loss and reliable digital and analog optical links for control and signal distribution. The use of optically controlled microwave devices as photodetectors, to provide gain control of an amplifier, and to injection lock an oscillator in phased array antenna applications is shown.

INTRODUCTION

As the operating frequency and speed of solid state devices and circuits increase, their applications in advanced space communications systems will require innovative solutions to control and interconnect these devices and circuits. At microwave and millimeter wave frequencies, the currently available transmission media (such as coaxial cables and waveguides) for systems interconnection is bulky and inflexible. Optical fiber has been suggested by several authors (refs. 1 and 2) as a viable alternative, providing light weight, low loss, small size, broad bandwidth and excellent isolation characteristic transmission media. Such fiber-optic links require the use of high frequency lasers and wide bandwidth photodiodes. Lasers and photodiodes can be integrated with other microwave devices on GaAs substrates to achieve small size. Optical fiber also can be used to directly illuminate a device or provide an interconnect via optical waveguide coupling as shown in figure 1. Such a direct optical control of microwave devices, demonstrated by De Salles (ref. 3), has the potential to provide gain control, photodetection and injection locking functions. In these experiments, a GaAs MESFET structure was used and optimum efficiency for coupling optical energy could not be achieved. Recent developments in heterostructures will allow researchers to change the composition and thickness of various active layers in microwave device structures for the optimization of optical and microwave functions in a single device. In this paper, the physical basis for the operation of an optically controlled microwave device is discussed. The effect of optical illumination on the dc and microwave characteristics of a GaAs MESFET and HEMT and the application of an optically controlled microwave device as a photodetector, to control gain of an amplifier and injection locking of an oscillator are

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reviewed. The integration of microwave and optical functions on a single GaAs substrate for circuit applications are also discussed.

PHYSICAL MECHANISM

Fundamentally, the optical response of a microwave device structure is based on photoconductive and photovoltaic effects; the relative contribution depends on the device and experimental parameters. When a microwave device is illuminated, optical absorption takes place in the device substrate material, the active layer, and the Shottky and ohmic contact materials, thereby increasing the free carrier density of the device due to a photoconduction effect. This is shown in figure 2. When potential bias between source and drain is applied, a photoconductive current flows.

Photovoltaic effect contributions to the optical response come from the potential barriers created due to gate and intrinsic layer interface, the buffer layer and substrate interface, and intrinsic layer doping density variations. As the applied gate bias controls the effective intrinsic layer thickness, the optical illumination modulates the FET intrinsic layer in a similar manner. The free carriers generated by illumination are collected in the high electric field of a space - charge region (refs. 4 and 5).

DC CHARACTERISTICS

As discussed earlier, electrons and holes are generated when the energy of the incident photons is greater than or equal to the forbidden gap bandwidth of a semiconductor device. When drain voltage is applied, the excess electrons and holes affects the transconductance characteristics of the device. Photoconductive effects and photovoltaic effects both have been considered to contribute to these changes. In figure 3 the current-voltage characteristic for the reverse-biased source gate junction for a GaAs MESFET and HEMT are shown. No bias is applied to the drain. The measurements were made by illuminating a low noise AlGaAs/GaAs HEMT (0.5 μm gate length) and a low noise GaAs MESFET (0.3 μm gate length) by an AlGaAs/GaAs Laser diode with a 50 μm multimode grade index optical fiber pigtail at a wavelength of 0.83 μm. The photovoltaic effect is clearly illustrated when the curves (I_G VS V_{GS}) obtained under illumination are extrapolated until the intersection of the x-axis. The light generated voltage (Vlit) obtained at the zero gate current is the same as if a forward bias between source and gate was applied. The generated voltages (Vlit), from figure 2, for a AlGaAs/GaAs HEMT and a GaAs MESFET are 0.57 and 0.24 V, respectively. The higher Vlit for the HEMT is attributed to the higher increase in hole concentration mainly due the absorption thickness d. (see eq. (1) in ref. 6).

The measured drain to source current (Ids) as a function of the drain to source voltage (VDS) with and without optical illumination, for an HEMT and a GaAs MESFET are shown in figure 4. The measured gain with and without optical illumination as a function of Vgs for an AlGaAs/GaAs HEMT and a GaAs MESFET are shown in figure 5. The gain increased by 2.5 dB at Vgs = -0.95 V at a frequency equal to 26.5 GHz when the HEMT was illuminated by 1.7 mW/cm^2 of optical power.

MICROWAVE CHARACTERISTICS

For GaAs MESFETS (refs. 3, 8, and 9) and HEMTS (ref. 7) it has been consistently demonstrated that light has an extremely small effect of S_{21}, S_{12} and S_{22} parameters. It has a significant effect on the S_{11} parameter. This case is illustrated for the HEMT in figure 6. From de-embedded device S-parameters, the decrease in the gate, as well as the drain capacitances, along with the decrease in the gate to drain feedback capacitance, under optical illumination, are observed. Gate charging resistance, R_1, and the channel resistance, R_0, both decreased with optical illumination. These results will allow an estimate of the performance of optically controlled MESFET and HEMT based amplifiers and oscillators.

MONOLITHIC INTEGRATION OF MICROWAVE AND OPTICAL FUNCTIONS

In the past several years, GaAs substrates have provided the basis for the development of monolithic microwave integrated circuit technology. Low loss microstrip lines can be fabricated on this semi-insulating substrate. The high electron saturation velocity provides the essential microwave device technology. At the same time optical waveguides, lasers and detectors can be fabricated on a GaAs substrates with convenient control of the composition and thickness of GaAlAs layers. Such variation is desirable for altering the energy band-gap and index of refractions. The feasibility of fabricating a microwave and an optical integrated circuit on the same substrate provides an opportunity for monolithic integration of both optical and microwave functions for advanced circuit applications (ref. 10). This quality is attractive for optically controlled phased array antenna applications in space communications to provide low weight and reduced complexity systems. As shown in figure 7, the optical fiber can be coupled through an aligner to an integrated photodetector on a GaAs monolithic microwave integrated circuit (MMIC). It is shown here that optically controlled microwave device structures (interdigitated photodetector) can demodulate an RF signal carried via an optical signal. It can also detect and amplify a gigabit digital signal to control phase shifter and amplifier gain functions in an MMIC transmit module. An optical integrated circuit which will control the phase shifting and amplifier gain function of an MMIC transmit module is being fabricated by Honeywell Inc. for the NASA Lewis Research Center (ref. 11).

APPLICATION OF OPTICALLY CONTROLLED MICROWAVE DEVICES

As A Photodetector

The initial observations of Baack, et al. (ref. 12) that GaAs MESFET devices are sensitive to a 0.82 μm wavelength, was followed by serious investigation of other researchers to determine the application of a GaAs MESFET as a wide-band photodector.

Gammel, et al. (ref. 13) fabricated interdigitated photoconductors to enhance light coupling and also to provide a structure for monolithic integration of such detectors with other GaAs MESFET devices. They also integrated an optical waveguide structure to optically control the GaAs MESFET.

Similarly, the HEMT structure has been recently investigated as a photo conductor (ref. 14). A higher level of optical gain is observed due to a layer absorption thickness greater than GaAs MESFET.

As A Variable Gain Amplifier

The gain of an amplifier can be optically varied by changes produced in transconductance of the device when illuminated. De Salles (ref. 3) has shown that up to a 2.5 dB change in gain can be observed when the GaAs MESFET is illuminated and gate voltage (Vg) is chosen close to the pinch off. Similar results were found by Simons, et al. (ref. 7) for a HEMT structure.

Injection Locking of an Oscillator

Phased array antennas, based on GaAs MMICs as transmit or receive modules, require frequency synchronization of local oscillators by injection locking. The fiber-optic link has been proposed to synchronize these local oscillators, using optical injection locking techniques. Direct injection locking of IMPATT (refs. 15 and 16) and GaAs MESFET (ref. 16) oscillators have been shown up to x-band frequencies. However the direct modulation of the semiconductor laser and the poor coupling of optical energy to the active regions of the device limits the use at higher frequencies.

Indirect optical injection locking uses demodulation of an RF-modulated optical signal by a high-speed photodiode, which is amplified and then electrically injected to the IMPATT or FET oscillator. Indirect optical injection locking of a free-running 38-GHz IMPATT oscillator has been demonstrated (ref. 17). Herczfeld and Daryoush describe in detail various injection locking techniques in this symposium proceedings.

CONCLUSIONS

The physical basis, as well as dc and microwave characteristics of optically controlled microwave devices have been described. The changes produced in the performance of microwave devices due to optical illumination can be applied to detect an RF modulated optical signal, to control gain of an amplifier, and to provide injection locking of an oscillator.

Recent developments in monolithic GaAs integrated circuit technology in microwave and optical frequency domains will enhance the application of optically controlled circuits, particularly for phased array antenna applications in space communications systems. In addition, base band signal processing and switching functions for high speed communications systems may utilize the optically controlled circuits to simplify system complexity and enhance system speed.

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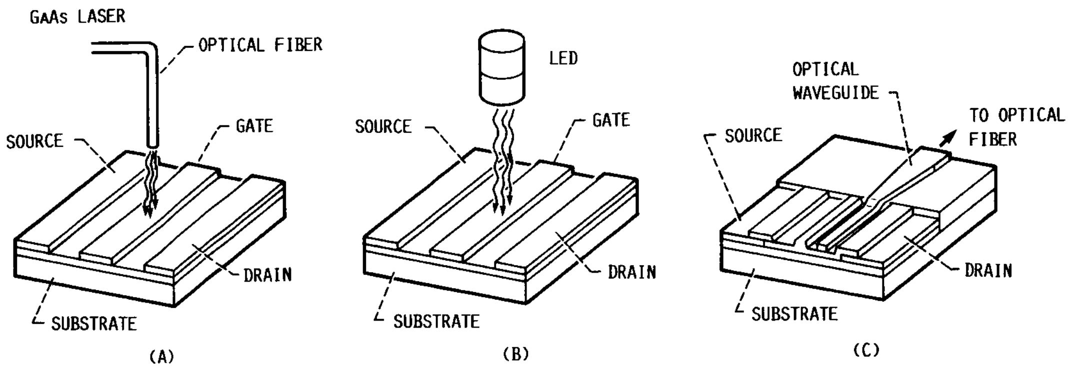


FIGURE 1. - TECHNIQUES FOR DIRECT OPTICAL CONTROL OF A MICROWAVE DEVICE. ILLUMINATION OF A MESFET STRUCTURE BY (A) AN OPTICAL FIBER (B) LED SOURCE (C) AN OPTICAL WAVEGUIDE.

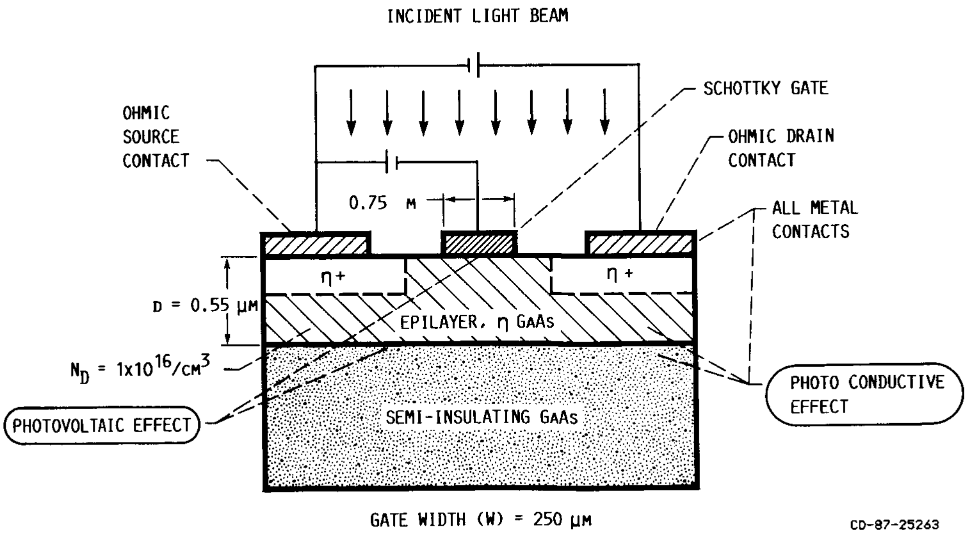
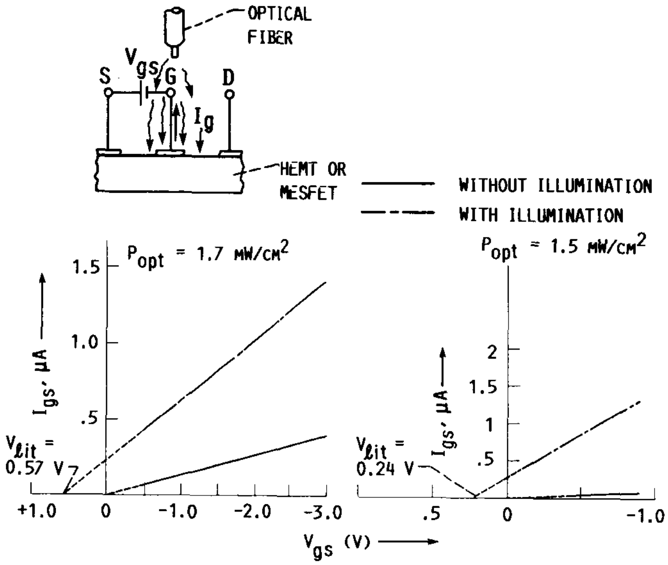


FIGURE 2. - PHYSICAL MECHANISM OF AN OPTICALLY CONTROLLED MESFET.



(A) DEVICE AlGaAs/GaAs HEMT (MODEL NO. MPD-H503); V_{ds} = 0 V.

(B) DEVICE GaAs MESFET (MODEL NO. RPX 2322); V_{ds} = 0 V.

FIGURE 3. - MEASURED GATE CURRENT (I_G) VERSUS GATE TO SOURCE VOLTAGE (V_{GS}). DRAIN IS KEPT OPEN. DISTANCE BETWEEN END OF FIBER AND DEVICE, (1MM).

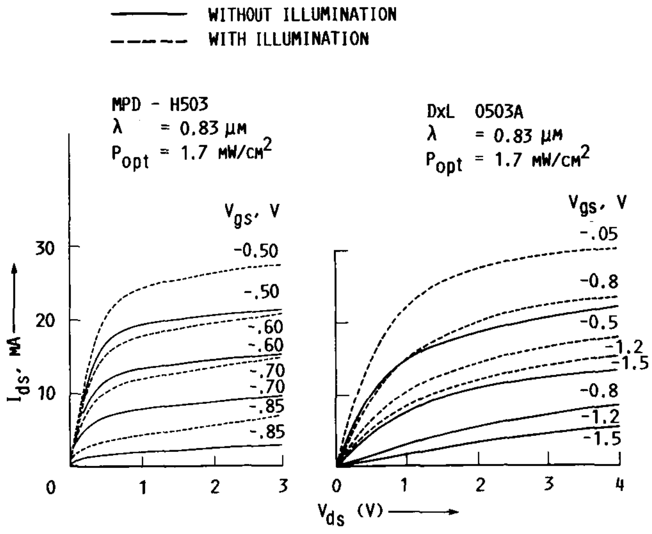


FIGURE 4. - MEASURED DRAIN CURRENT (I_{DS}) VERSUS DRAIN VOLTAGE (V_{DS}) WITH AND WITHOUT ILLUMINATION.

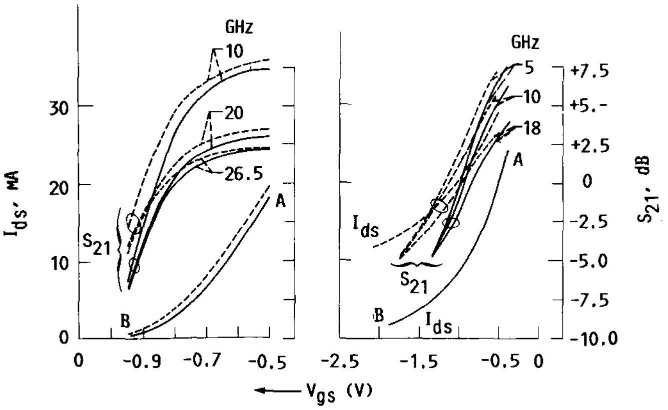
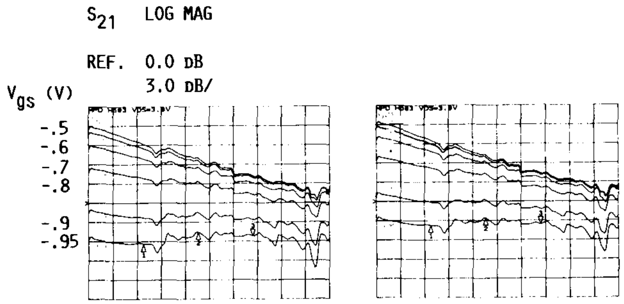
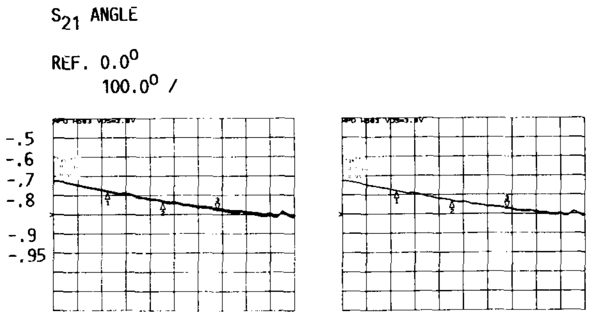


FIGURE 5. - MEASURED DRAIN VERSUS GATE TO SOURCE VOLTAGE (VGS) WITH AND WITHOUT ILLUMINATION.



(A) S_{21} MAGNITUDE WITHOUT OPTICAL ILLUMINATION.

(B) S_{21} MAGNITUDE WITH ILLUMINATION.



START 0.045 GHz
STOP 26.500 GHz

(C) S_{21} PHASE WITHOUT OPTICAL ILLUMINATION.

(D) S_{21} PHASE WITH OPTICAL ILLUMINATION.

FIGURE 6. - MEASURED S_{21} PARAMETERS FOR ALGAAS/GAAS HEMT.

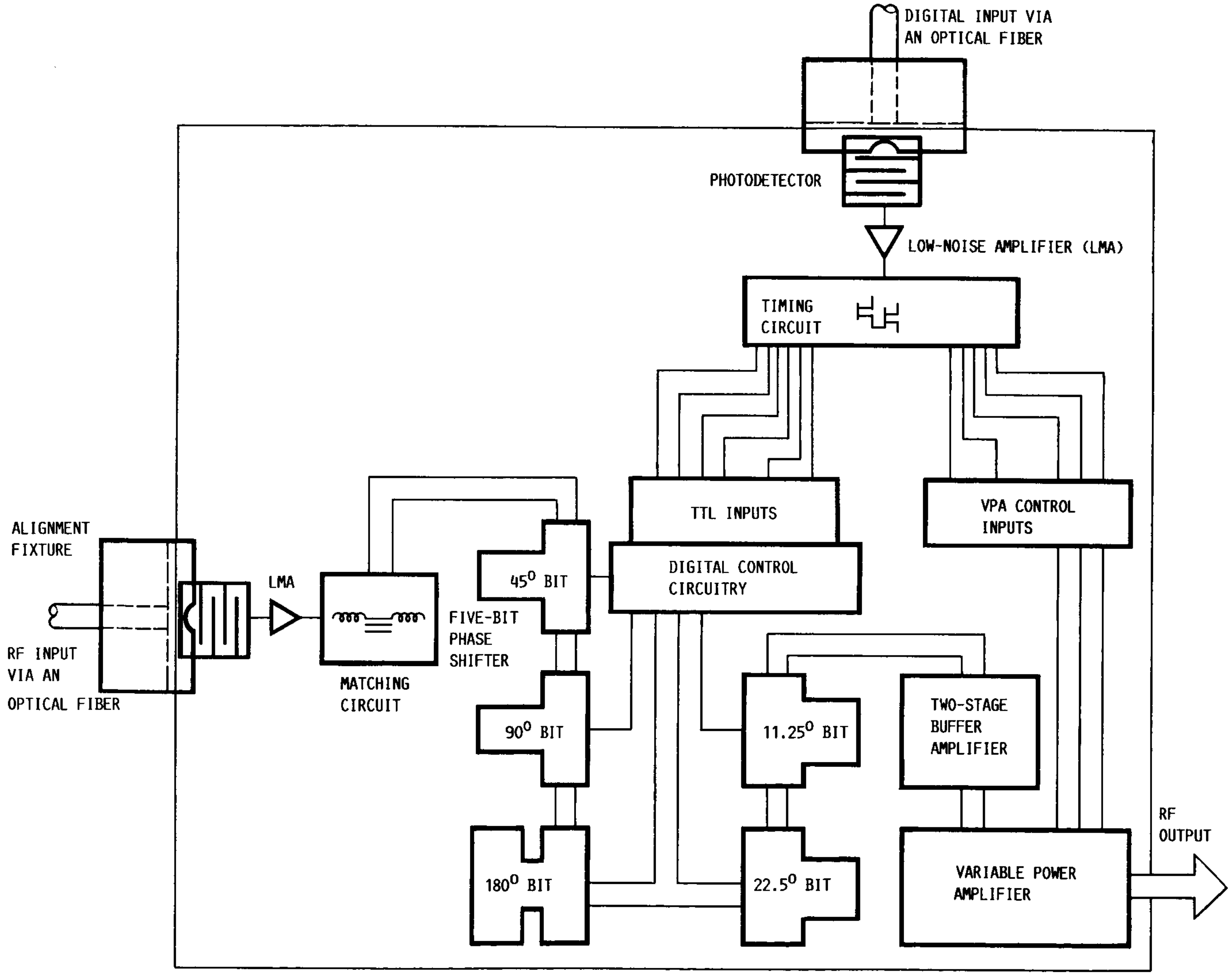


FIGURE 7. - GAAS INTEGRATED WITH HIGH FREQUENCY/HIGH SPEED PHOTODETECTORS FOR ANALOG AND DIGITAL FUNCTIONS INTERFACE VIA AN OPTICAL FIBER.

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16. Abstract

Optical control of microwave devices and circuits by an optical fiber has the potential to simplify signal distribution networks in high frequency communications systems. In this paper, we compare the optical response of two terminal and three terminal (GaAs MESFET, HEMT, PBT) microwave devices and examine several schemes for controlling such devices by modulated optical signals. Monolithic integration of optical and microwave functions on a single semiconductor substrate is considered to provide low power, low loss, and reliable digital and analog optical links for signal distribution.

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