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# DETECTION OF RADIO-FREQUENCY MODULATED OPTICAL SIGNALS BY TWO AND THREE TERMINAL MICROWAVE DEVICES

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## SUMMARY

An interdigitated photoconductor (two terminal device) on GaAlAs/GaAs heterostructure was fabricated and tested by an electro-optical sampling technique. Further, the photoresponse of GaAlAs/GaAs HEMT (three terminal device) was obtained by illuminating the device with an optical signal modulated up to 8 GHz. Gain-bandwidth product, response time, and noise properties of photoconductor and HEMT devices were obtained. Monolithic integration of these photodetectors with GaAs microwave devices for optically controlled phased array antenna applications is discussed.

## INTRODUCTION

The use of analog and digital fiber optic links to provide RF feed, phase control, amplitude control, and injection locking of oscillators in GaAs MMIC elements for phased array antenna systems is being considered to reduce weight, size, and crosstalk (ref. 1). Such links require transmitters and receivers. For a large array, discrete receivers bonded to GaAs MMIC, will add to the problem rather than provide the solution. However, integrated optical receivers whose structure is compatible with GaAs MMIC and which can be fabricated using standard techniques, will provide small size, single package element.

Experimental studies to optically control GaAs MESFET, have shown that such devices have the potential for optical detectors (refs. 2 to 6) and their structures are compatible with GaAs MMICs. Photoconductors using GaAs MESFET like structures have also been studied (refs. 7 to 8). Interdigitated surface geometrics used in these photoconductors have shown improved optical coupling efficiency and reduced alignment problems to these devices.

Recently, optical control of HEMT structures (ref. 9) and HEMT photodetectors (refs. 10 and 11) have also been demonstrated. In this paper, HEMT photodetector with interdigitated surface geometries are presented in section III. Detection of RF modulated optical signal by GaAlAs/GaAs HEMT is

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discussed in section IV. Monolithic integration of optical and microwave functions is discussed in section V and, finally, conclusions are presented in section VI.

## 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 1. 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. 3 to 12).

## INTERDIGITATED HEMT PHOTOCONDUCTOR

### Detector Structure and Fabrication

The interdigitated HEMT photoconductive detector structure used for fabrication is shown in figure 2. The photoconductor is square with 50-μm sides. The ohmic contact length is 3 μm, and two different detectors with the gap spaces of 2.5 and 5 μm respectively have been fabricated. The vertical HEMT structure (shown in fig. 3) consists of 1.20 μm thick undoped GaAs layer, grown by MBE technique on semi-insulating GaAs substrate. A GaAlAs spacer layer of 40 A° thick is deposited on GaAs layer, followed by 400 A° thick tests, the devices were mounted on and either ribbon bonded or silver epoxied to a modified SMA end launcher of the type used for the microstrip transmission line transition to coax. An 800 nm GaAlAs laser 32 ps FWHM pulses was used to measure the time domain response of the various detectors. Quantum efficiency measurements were made by comparing the detectors with the discrete GaAs/GaAlAs PIN reference detector.

### Experimental Results

An I-V curve of the detector, a symmetric device, is shown in figure 4. The operation of this device is independent of bias polarity. The initial linear slope of the curve around the origin closely corresponds to the theoretical low field bulk resistance between the ohmic contacts, and is about 10 Ω.

The high field saturation is caused by a combination of carrier velocity saturation and channel pinch-off. The slope, and therefore the detector resistance at dc, is seen in figure 4 to be a function of the bias, starting at a low value of resistance for small bias, with the resistance smoothly increasing until it becomes large at high bias. The responsivity of 4.4 A/W was achieved at 800 nm wavelength.

The measured impulse responses are shown in figure 5(a). The area under the response curves of figure 5(a) is proportional to quantum efficiency, ($\eta$). the number of carriers collected by the external load (50 Ω) divided by the number of incident photons. This definition allows $\eta$ to be greater than unity in the case of the photoconductor because of the photoconductive gain. The measured $\eta$ is 41.

Since the response time is compared to the optical pulse width (32 ps), the output is a good approximation to the detector impulse response and the frequency domain response is determined from the fast Fourier transform of the digitized impulse response (fig. 5(b)). The photodetector (with 2.5 m spacing) has a gain-bandwidth product of 6.82 GHz. Further, it also has a high gain of 41, but suffers from a low effective bandwidth of about 170 MHz (fig. 5 (ref. 6)).

## GaAlAs/GaAs HIGH ELECTRON MOBILITY TRANSISTOR

### Experimental Setup

A low noise AlGaAs/GaAs high electron mobility transistor (MPD-H503, Gould, Inc.) with recessed Pi-gate of length 0.5 μm and width 280 μm, is used for this experiment. For optical illumination an AlGaAs/GaAs laser diode (SL-620 S, Ortel Corp.) with a fiber pigtail, which operates at a wavelength of 0.83 μm and has a direct modulation bandwidth of 10 GHz is used. The optical power emitted from the 50/125 μm multimode graded index optical fiber pigtail as measured using a calibrated digital power meter and a photosensor (815, Newport Corp.) is 1.7 nW. The tip of the fiber is held at a distance of 1 mm from the device.

These devices are mounted on a 0.375 by 0.375 in., 25 mil thick alumina carrier. The alumina carrier also accommodates a pair of 50 Ω coplanar waveguides (CPW) which serve as the signal input and also output ports. The device gate and drain pads and the source pad are wire bonded to the CPW center strip conductors and the ground plane respectively. The carrier is then mounted in a test fixture (Design Techniques, Inc. ) which has two 3.5 mm coaxial connectors for external connection. The test fixture also has provision for ensuring repeatable pressure contact between the terminals of the CPWs on the carrier and the two 3.5 mm coaxial connectors on the fixture. A CPW calibration kit consisting of a 50 Ω through, two short circuits, and an open circuit on similar alumina carriers are used for calibrating the HP8510 automatic network analyzer and de-embedding the device S-parameters.

### Experimental Results

The light generated voltage, $V_{lit}$, is obtained by plotting the measured gate current $I_g$ as a function of the reverse biased gate to source voltage $V_{gs}$, and extrapolating the graph until it intersects the X-axis. The intersection point is read as the light generated voltage, which from figure 6 for a AlGaAs/GaAs HEMT is 0.57 V. An experiment was conducted by illuminating the HEMT device with an optical signal which had been modulated with a 8 GHz RF signal. The detected 8 GHz output was observed on a spectrum analyzer and is shown in figure 7. For the purpose of displaying on a spectrum analyzer and external amplifier with a gain of 20 dB was added. The HEMT has a responsivity of 3.53A/W with $V_{gs} = -0.55$ and $V_{ds} = 3.0$ V.

## 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 integration of both optical and microwave functions for advanced circuit applications (ref. 13). This quality is attractive for optically controlled phased array antenna applications in space communications to provide low weight and reduced complexity systems. 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 or an analog 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. 14). In a MESFET process, Wojtczuk i.e. (ref. 15) have fabricated a monolithically integrated photoreceiver to illustrate the feasibility and ease of integrating these detectors.

## CONCLUSIONS

It is well known that HEMT devices have an advantage over the GaAs MESFET because of the higher electron mobility in undoped GaAs layer compared to the doped GaAs used in GaAs MESFETS. However, in case of photodetectors discussed in this paper, the main advantage observed is the higher absorption thickness (1 μm GaAs) available in the HEMT structures which increases gain and coupling efficiency. Due to trapping of the holes in the substrate, the optical response showed slow tail (fig. 5(a)). It is possible to design a structure where the minority carriers that is the holes can be "picked".

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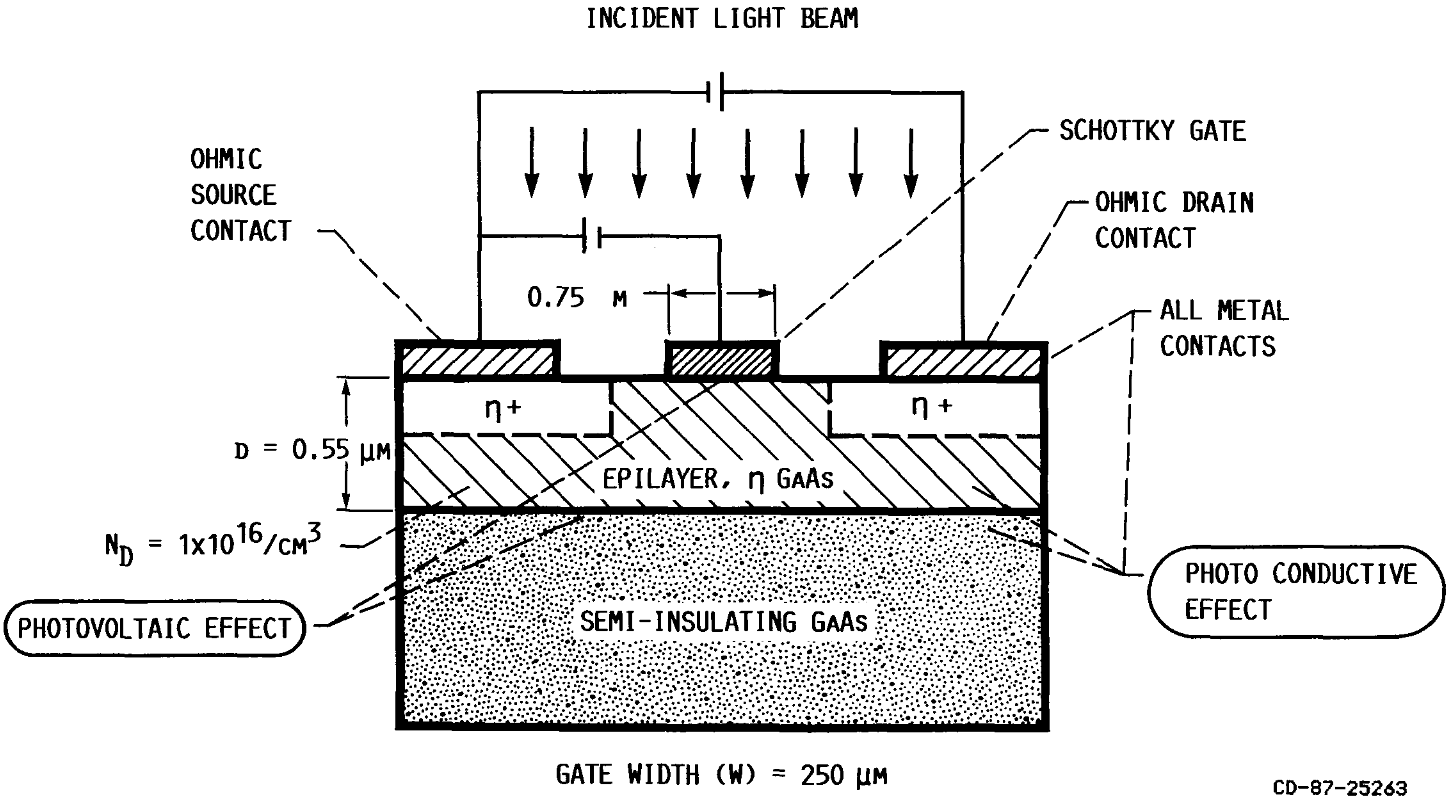


FIGURE 1. - PHYSICAL MECHANISM OF AN OPTICALLY CONTROLLED MESFET.

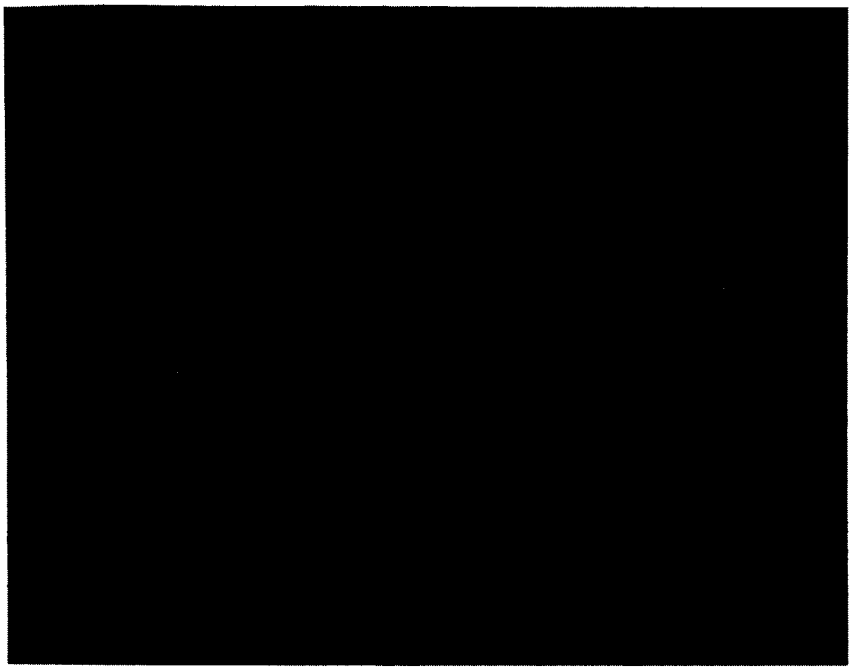

FIGURE 2. - 50 μm x 50 μm, INTERDIGITATED PHOTO CONDUCTIVE DETECTOR.

HEMT PHOTOCONDUCTOR STRUCTURE

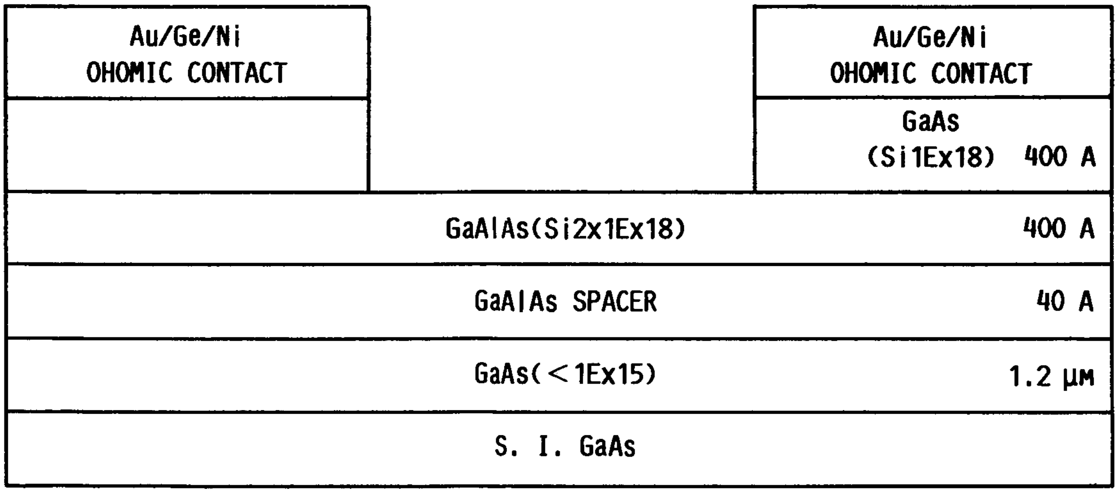


FIGURE 3. - VERTICAL MATERIAL STRUCTURE OF HEMT PHOTOCONDUCTOR.

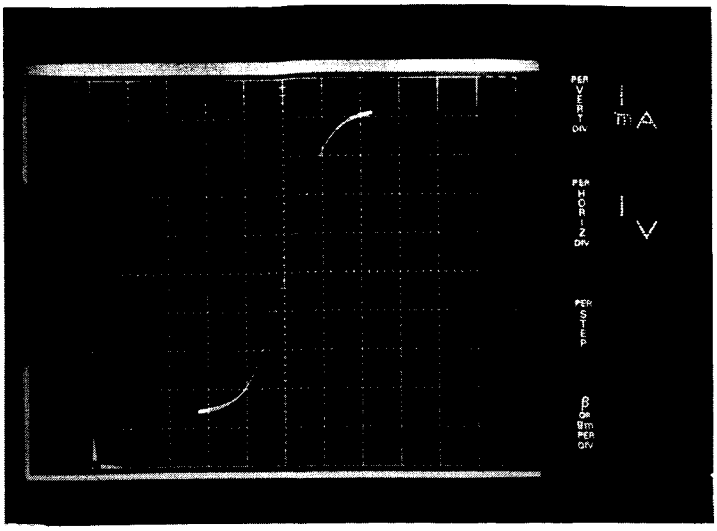


FIGURE 4. - I-V CURVE OF HEMT PHOTOCONDUCTOR.
VERTICLE: 1 MA/DIV, HORIZONTAL; 1V/DIV.

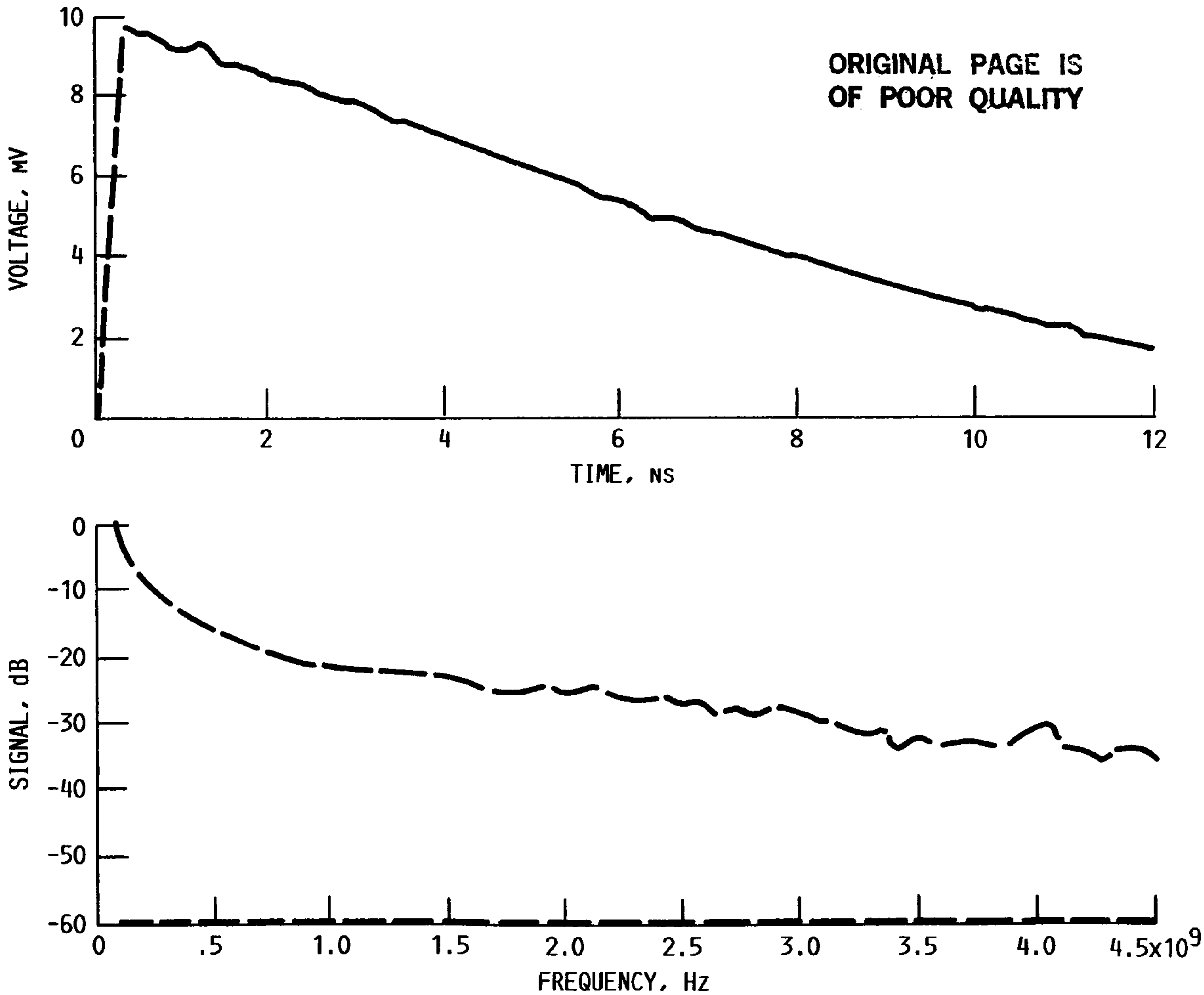


FIGURE 5. - TIME (A) AND FREQUENCY RESPONSE (B) OF AN HEMT PHOTOCONDUCTOR.

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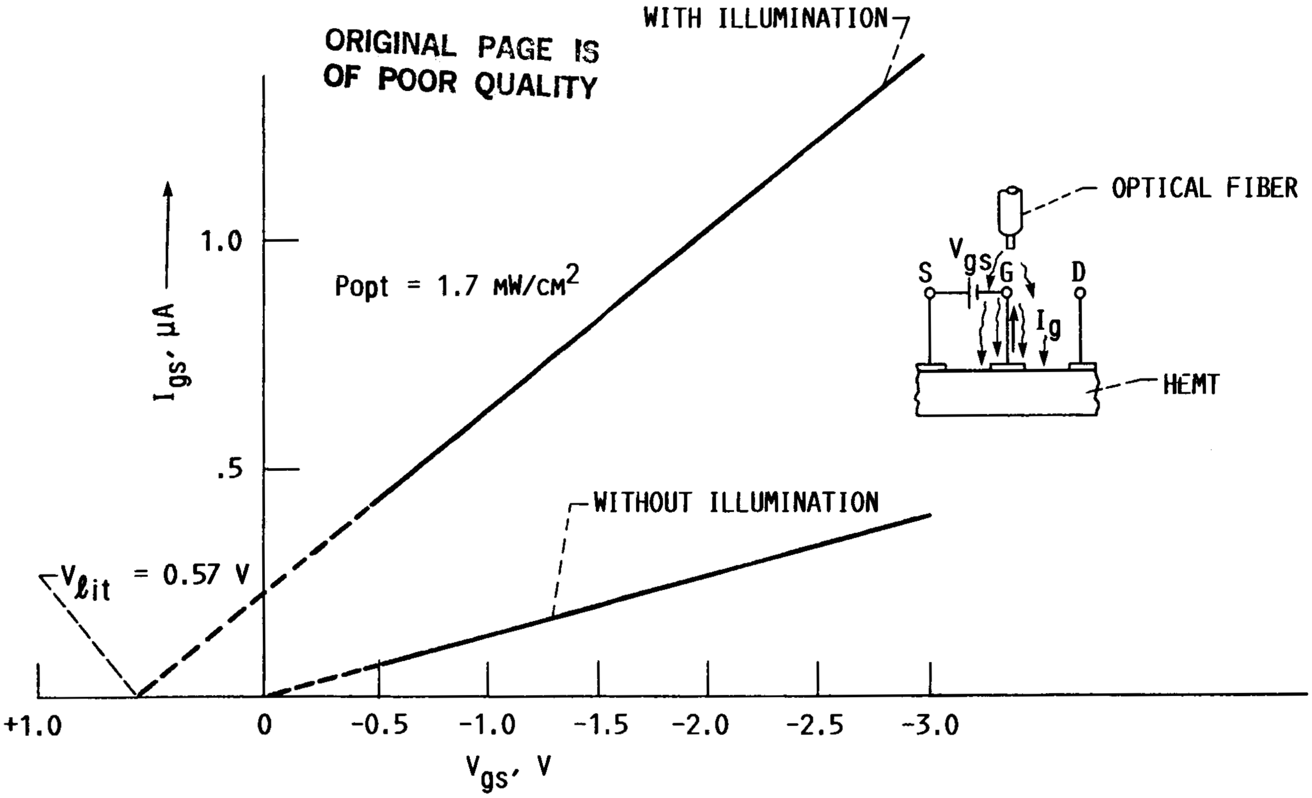


FIGURE 6. - MEASURED GATE CURRENT ($I_G$) VERSUS GATE TO SOURCE VOLTAGE ($V_{GS}$). DRAIN IS KEPT OPEN. DISTANCE BETWEEN END OF FIBER AND DEVICE IS 1 MM.

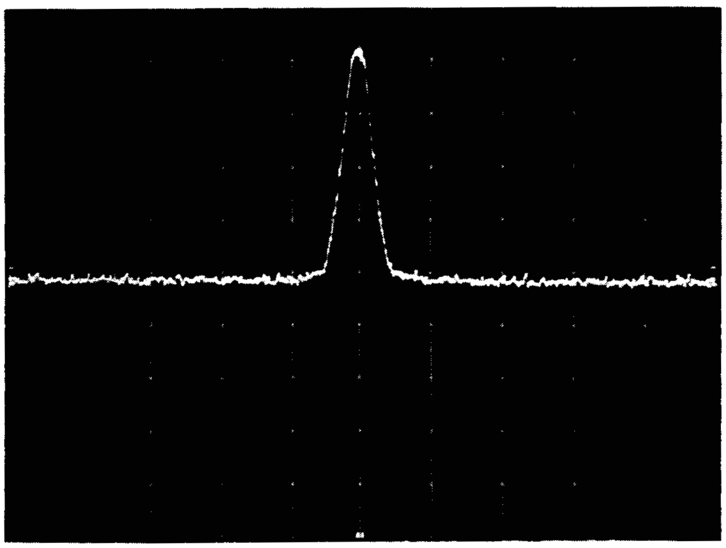

FIGURE 7. - DETECTED 8 GHz SIGNAL.

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16. Abstract

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