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Optical Control of Microwave Circuits for Active Phased Array Radars

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Combining GaAs Microwave Monolithic Integrated Circuits (MIMICs) and fiber optic technologies offers microwave system designers many advantages for remote antennas, communication links, and phased array antennas. Fiber optic transmission systems have become an attractive alternative for the distribution of microwave and control signals, because of their desirable features, such as high speed, large bandwidth, good electrical isolation, small size, and their immunity to electromagnetic interference (EMI) and electromagnetic pulse (EMP). Presented in this report are four optically controlled microwave circuits, which take advantage of the GaAs MESFET as an optical detector, to demonstrate that fiber optic technology can be integrated into GaAs MMIC based microwave systems.

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1. INTRODUCTION

Combining GaAs Microwave Monolithic Integrated Circuits (MMICs) and fiber optic technologies offers microwave system designers many advantages for remote antennas, communication links, and phased array antennas. Active phased array antennas use a large number of individually controlled transmit-receive (T/R) modules which require independent microwave reference and control signals. The resulting distribution networks needed to route this information for T/R modules to perform beam steering and shaping can become very complex. Conventional distribution networks such as coaxial transmission lines and metallic waveguide are bulky, and are susceptible to radiation in hostile environments. Fiber optic transmission systems have become an attractive alternative for the distribution of microwave and control signals, because of their desirable features, such as high speed, large bandwidth, good electrical isolation, small size, and immunity to electromagnetic interference (EMI) and electromagnetic pulse (EMP). Presented in this report are four optically controlled microwave circuits, which take advantage of the GaAs MESFET as an optical detector, to demonstrate that fiber optic technology can be integrated into GaAs MMIC-based microwave systems.

2. GaAs MMIC MESFET AS AN OPTICAL DETECTOR

For microwave applications, there is an interest in linking optical signals directly to the MMIC. This makes the MESFET, the principal building block of MMICs, an attractive optical detector because, unlike the PIN diode, it is compatible with basic MMIC processing. The Metal-Semiconductor (MS) photodetector, which performs similarly to the PIN diode, can also be fabricated on the MMIC chip. However, for many applications, such as the direct optical injection locking of oscillators, the illumination of an active device is required.

The photoresponse of the MESFET is due to the photogenerated currents produced in the channel, substrate, gate depletion region, and potential barrier at the channel substrate interface. The photoresponse of an ITT GaAs MESFET as a function of gate-to-source voltage (Vgs) for different optical intensities is shown in Figure 1. From the graph two important observations can be made. First, the photoresponse is an increasing function of the optical intensity due to the increase in the photogenerated carriers in the device. Second, the photoresponse is dependent on the electrical bias. For the MESFET, the optimum bias corresponds to the maximum device transconductance (g_m).

The frequency response of an ITT GaAs MESFET and a PIN photodetector was compared by measuring the forward transmission coefficient, $|S21|$, of each in a

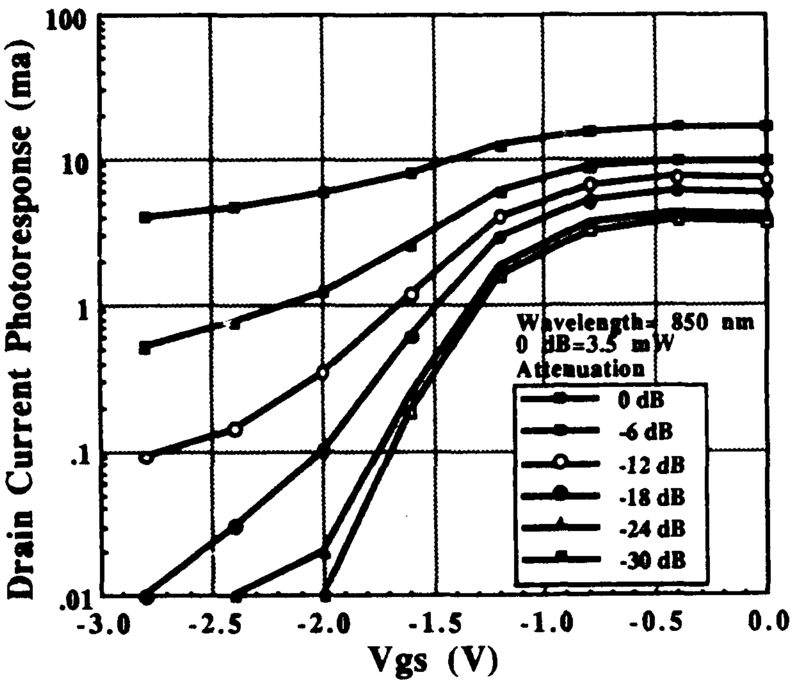

Figure 1. Photoresponse of a GaAs MESFET as a function of Vgs and optical intensity.

fiber optic link. The frequency responses of the MESFET and the PIN are depicted in Figure 2, showing that the ITT device response is higher than the PIN almost to 1 GHz.

The MESFET has a larger response than the PIN diode, even at significantly lower coupling efficiencies (13.5% for the ITT device and 60% for the PIN), because of internal gain mechanisms. Improvements in optical coupling and optimization of material parameters of the MESFET will lead to improvements in frequency response, so that it will equal or better the performance of the PIN to a few GHz.

3. OPTICAL CONTROL OF MICROWAVE CIRCUITS

The MESFET is used as an optical detector in two types of control configurations, direct and indirect, to perform optical control of microwave circuits. In the indirect approach, the MESFET is used as an optical detector to receive a control signal which is sampled, amplified, and then utilized to control

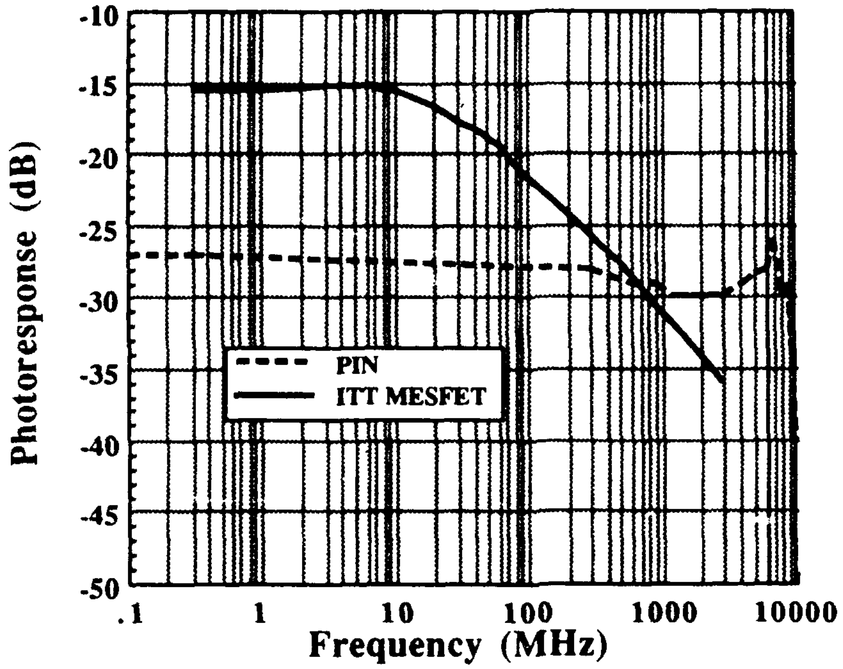

Figure 2. Frequency response of a PIN photodetector and an ITT GaAs MESFET.

microwave circuit functions. In the direct approach, the optical signal illuminates the MESFET and changes the device's operating conditions. Three indirectly controlled circuits for phase, gain and switching, and one directly controlled circuit for injection locking, were built to demonstrate optically controlled microwave functions.

3.1 OPTICAL GAIN CONTROL

Gain control by optical means has been accomplished [1,2] by controlling the biasing circuit of an amplifier, as shown in the block diagram in Figure 3. For this experiment, the optical sensing element was a multi-finger MESFET, which was illuminated by an LED source. The optical signal changed the drain to source voltage of the MESFET, which in turn was used to control the bias voltage of the amplifier.

The gain control element was a MMIC distributed amplifier whose performance was controllable through its bias voltage. A 14-gate finger MESFET served as an optical detector. By using a multi-finger MESFET, the exposed GaAs area for

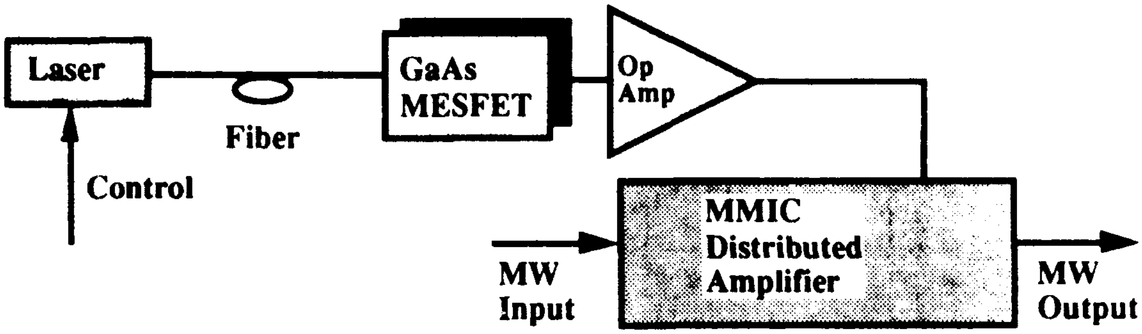

Figure 3. Block diagram of an optically controlled amplifier.

light absorption was increased resulting in a significant improvement in the optical response over a single finger device. Gain control was established by increasing the light to the MESFET. As the optical illumination incident on the MESFET was increased, the gain of the distributed amplifier increased. A change in gain of -10 dB to +5 dB was achieved over the frequency range of 5 to 8 GHz with only 250 μw of optical power, as shown in Figure 4.

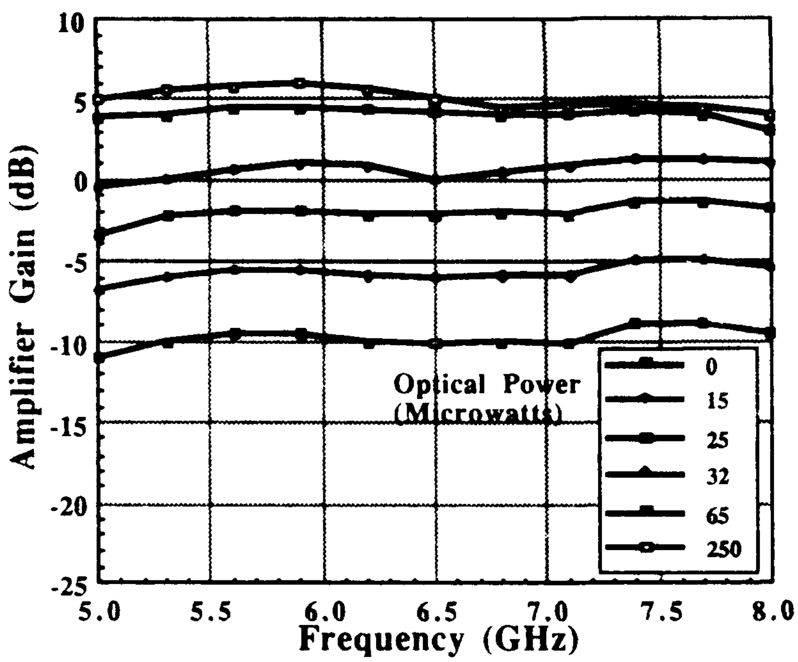

Figure 4. Amplifier gain as a function of optical power.

3.2 OPTICAL PHASE CONTROL

The optical control of a 6-bit X-band phase shifter was also demonstrated [3]. A digital phase shifter consisting of n-bits may be optically controlled by an intensity modulated LED or laser diode. Again a MESFET was used as the optical detector in this experiment. The LED's intensity was varied to produce 2n equally spaced discrete MESFET output voltages, which were appropriately scaled via a standard amplifier to correspond to an A/D converter input voltage range. The A/D converter then converted the voltages to an n-bit binary word which was used to command the phase shifter to a desired phase state. In this way, the intensity level of the incident optical input sets the phase shifter to the desired state. A block diagram of the phase shifter is shown in Figure 5 and the test results at 10 GHz are shown in Figure 6.

3.3 OPTICAL SWITCHING

An optically controlled GaAs MMIC switch was constructed and tested with the MESFET as an optical detector [4]. A block diagram of the circuit is shown in Figure 7. The microwave switch, contained on a single GaAs MMIC chip, was a single pole double throw (SPDT) which operated from 8 to 12 GHz. The switch was controlled by two voltage settings, V_1 and V_2. To switch the microwave input signal to OUTPUT 1, the required voltages were V_1=0.0 and V_2=-7.0 volts. To switch the microwave input signal to OUTPUT 2, the voltages needed were V_1=-7.0 and V_2=0.0 volts.

The operation of this circuit is as follows. The MESFET optical detector was biased at pinch-off, and the drain-to-source voltage (V_{DS}) was set to 3.0 volts. Under optical illumination the device conducted current through R_D which resulted in a change of 0.5 volts in V_{DS}. The optical intensity needed to provide the 0.5 volt change was only 25 μw. The drain of the MESFET was connected to two high speed operational amplifiers with a voltage gain of 14 (23 dB). One of the amplifiers operated in the inverting mode and the other in the non-inverting mode. In the absence of illumination, the difference between V_{DS} and the reference voltage to the input of the non-inverting op-amp, V_{ref1}, was 0.0 volts, and therefore the output voltage V_1 was 0.0 volts. For the inverting op-amp the difference was 0.5 volts at the input, V_{ref2} was set to 2.5 volts, and with a gain of 14, the output V_2 was -7.0 volts. Under these conditions, OUTPUT 1 was in the low loss state, and OUTPUT 2 was in the isolation state. When the MESFET was illuminated, V_{DS} changed from 3.0 to 2.5 volts and the outputs of the op-amps switched states, thereby switching the microwave signal from OUTPUT 1 to OUTPUT 2. Switching rates of 100 ns were obtained.

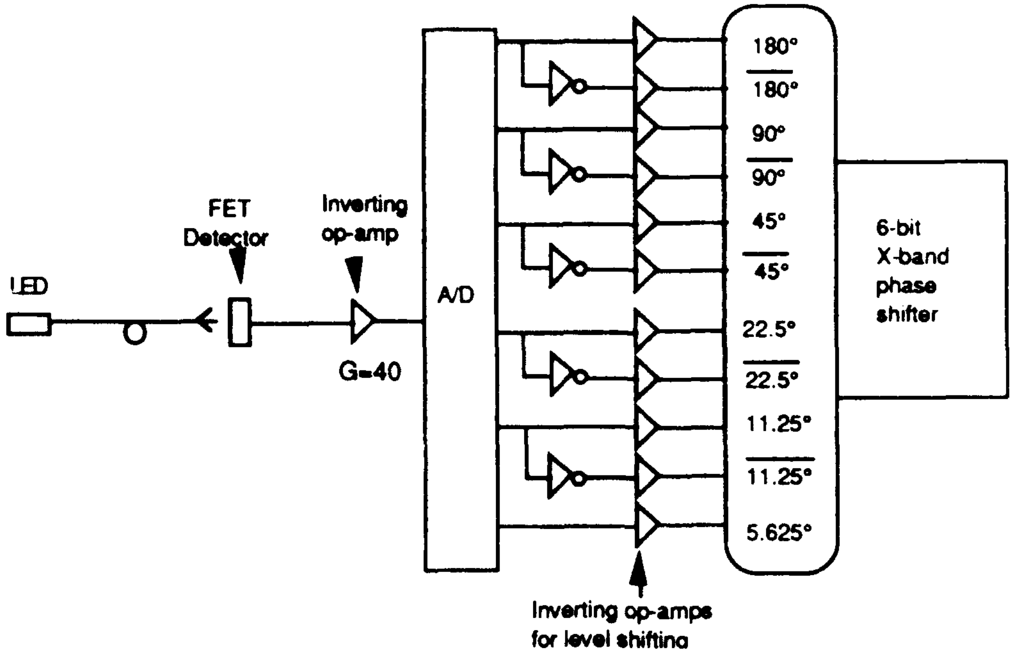

Figure 5. Block diagram of an optically controlled 6-bit X-band phase shifter.

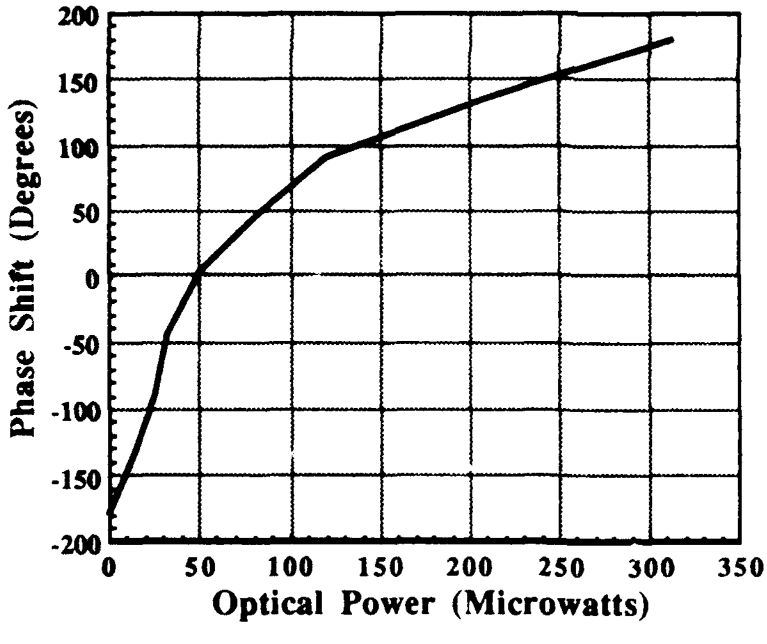

Figure 6. Phase shift as a function of optical power for the X-band digital phase shifter at 10 GHz.

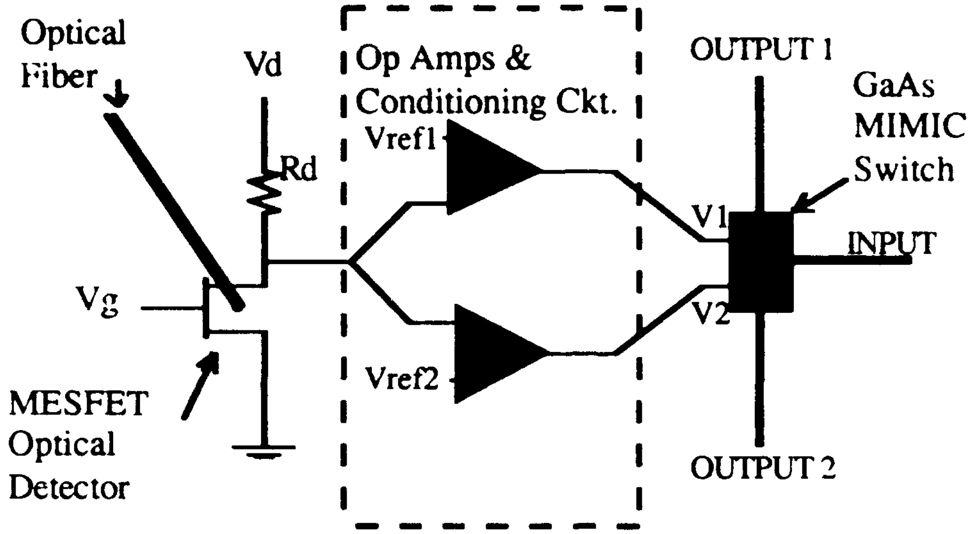

Figure 7. Optically controlled GaAs MMIC switch.

3.4 DIRECT OPTICAL INJECTION LOCKING

Each individual T/R module needs its own phase and frequency reference signal. A high speed fiber optic link can be employed to provide this reference signal by optically injection locking an oscillator in the module. In direct optical injection locking, the active element in the oscillator is illuminated by an optical signal which contains a microwave modulation. The direct method is a simple technique which is easily integrated into MMICs.

For this experiment, an oscillator was designed using a MESFET with a large drain to source spacing to improve optical coupling [5]. The oscillator was designed in a common gate configuration with series inductive feedback. The circuit was fabricated on an alumina substrate with the MESFET chip mounted to allow direct illumination from an optical fiber. The free running unilluminated oscillator, with an output power of 3.7 mW, operated at a frequency of 5.458 GHz. A high speed laser, coupled to a 50μm core fiber, was biased to 4 mW of output power and modulated to approximately 100% modulation depth, at a frequency close to that of the oscillator. The end of the fiber was positioned above the MESFET, and the optical signal injection locked the oscillator. Locking bandwidths of up to 50 MHz were achieved. Figures 8a and 8b show the MESFET oscillator in free running and optically injection locked states. This technique provides reasonable locking bandwidth without the need to separately detect and amplify the optical signal.

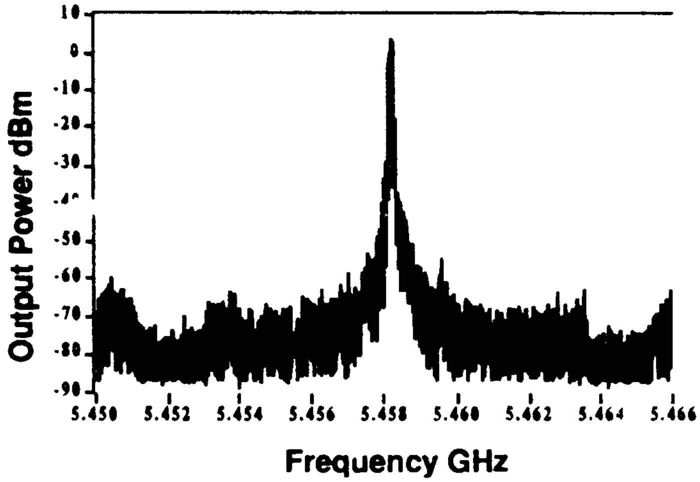

Figure 8a. Spectrum of the free running MESFET oscillator.

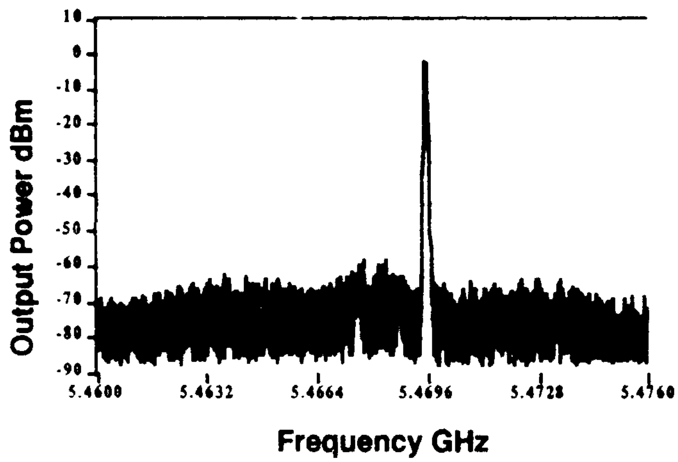

Figure 8b. Spectrum of the direct optically injection locked MESFET oscillator.

4. CONCLUSION

There is increasing interest in using fiber optics in microwave systems for distributing microwave signals, modulation information, and control signals, and for signal processing. Of particular interest is the use of fiber optics in GaAs based MMIC active phased array antennas. The distribution of microwave signals has been demonstrated as was the optical control of gain, phase and switching functions of microwave MMICs. These applications can be used to steer and shape the radiation pattern of active phased array antennas. Although the optimization of these circuits requires further investigation, the initial results are encouraging. In the area of MMICs, it is foreseen that future work will address the integration of electrooptic and microwave components on the same chip.

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