OPTICAL RESPONSE of the GaAs MESFET at MICROWAVE FREQUENCIES and APPLICATIONS

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Abstract

This paper concerns the MESFET as an optical port on MMICs. It has three principal themes: to show quantitatively how better optical coupling improves the photoresponse of the MESFET, to point out that by modest redesign its frequency response can be significantly extended up to 10 GHz, and finally to demonstrate how these can be converted to better optical control of MMIC circuits. A direct optical injection locking of a MESFET oscillator was performed.The measured optical injection locking bandwidth was 43.8 MHz.

Introduction

As microwave circuits and systems become more complex the efficient distribution of microwave and control signals gains importance. Optical technology is now being developed to distribute microwave signals for phased array antennas, antenna remoting, and delay lines. For microwave applications, there is a strong interest in linking of the optical signals directly to the MMIC. Previous investigations have involved experimentation with the MESFET as an optical detector for the control of circuits [1-3] and for the detection of microwave signals [4-6]. Researchers have also modeled the optical response of the device [7-8].

The MESFET is favored over the PIN diode or the metal semiconductor (MS) diode as an optical port because the inclusion of the PIN on the MMIC chip not only requires additional processing steps and higher cost but also offers less reliability. The MESFET is also favored over the MS structures because, (1) it exhibits substantially higher gain (to about 1 GHz), which is important to control applications, (2) it is used as an active element, allowing for the direct optical control of oscillators or amplifiers.

In this paper, we compare two different MESFETs with different optical coupling efficiencies, with a PIN diode. We also derive an expression for the RC time constant of the MESFET, which limits its high frequency performance. On the basis of these results, we predict that, by increasing the coupling efficiency and by reducing the RC time constant, the photoresponse of the MESFET can be equal to or better than that of the PIN diode up to 10 GHz.

Frequency Response of the MESFET to Optical Excitation

The frequency responses of two conventional GaAs-MMIC MESFETs and a PIN photodetector were compared by measuring the forward transmission coefficient, $|S_{21}|$, of a fiber optic link. For this measurement the output from a HP 8510B network analyzer (Port 1) was connected to a high speed laser (Ortel SL-1020). The microwave input signal to the laser was set to 0 dbm, resulting in a modulated optical power of 0.523 mw. The output of the laser was coupled to a 50 μm core fiber optic cable and routed to the high speed PIN photodetector (Ortel PD-025), the output of which was fed to the network analyzer (Port 2). This established a baseline high speed fiberoptic link.

In subsequent measurements, the two MESFETs were substituted for the PIN detector. Placing an resistor in the gate circuit, as commonly done, significantly enhances the optical sensitivity of the MESFET (external photovoltaic effect), albeit at the expense of the frequency response. In the present experimentation, the external resistor was omitted.

The two devices (Fujitsu FSX 51X and an ITT GTC 213-1) were selected because they exhibited nearly identical physical, electrical, and microwave characteristics but had significantly different optical coupling

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efficiencies. The Fujitsu device had two 150 μm gate fingers and the ITT sample had four 75 μm gate fingers (a total of 300 μm gate width for each). The frequency response of the MESFETs and the PIN is depicted in Fig. 1,which shows that the ITT device response is at least 5 db higher than the Fujitsu. The difference is attributed to better optical coupling. for evaluation of the coupling efficiencies, the optical radiation pattern emitted from a multimode fiber, which is a Gaussian density function, is integrated over the active areas of the FETs. The calculated coupling efficiencies for the Fujitsu and ITT devices were 5% and 13.5% respectively. The coupling efficiency for the PIN was approximately 60%. Improving coupling to the MESFET by altering the geometry of the device (shorter but larger number of gate fingers), by providing an elliptical spot size (cylindrical lens) and by using an antireflection coating boosts the MESFET photoresponse. This can can be achieved without adversely affecting the normal MMIC processing. In addition. increasing the source to drain spacing, as was the case for the ITT device, also increases the coupling.

Our measurements also revealed that the photoresponse for the optical powers used (2 to 10mW) is approximately a linear function of light intensity. Therefore, we estimate that a modest 3 dB increase in optical coupling would raise the microwave gain, and hence the photoresponse, of the MESFET by 6 dB. In effect increased optical coupling would move the response curve upward, but would not change its shape.

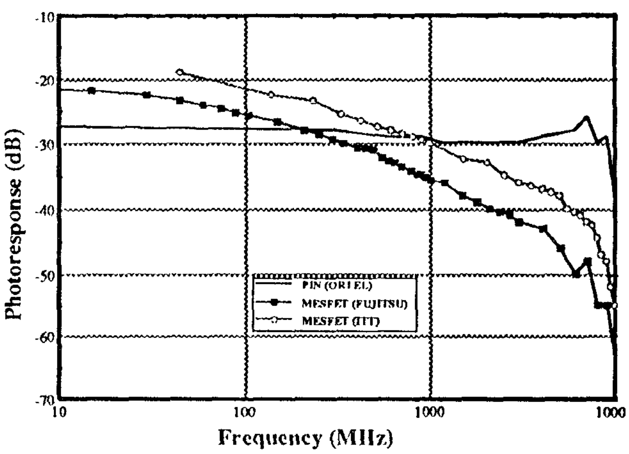

Figure 1. Frequency response of the high speed fiberoptic link with a PIN diode and with the ITT and Fujitsu MESFETs.

At lower frequencies the MESFET has a significantly larger response then the PIN diode, even at significantly lower coupling efficiencies, because of internal gain. In the absence of external resistor in the gate circuit, the gain is due to the internal photovoltaic effect, caused by the photo-induced barrier change between the epitaxial layer and the substrate, which modulates the channel height. The crossover frequencies between the PIN diode and the Fujitsu and ITT MESFETs are 250 and 1000 MHz respectively, as shown in Fig.1. The frequency response of the MESFET is limited by the RC time constant associated with the barrier. The barrier capacitance per unit area is ε/Δ, where Δ is the barrier thickness, a function of the doping ratio between the epi layer and the substrate as well as the doping profile in the interface region. The resistance is a combination of the substrate and barrier resistivities. The theoretical 3 dB cutoff fequency for the internal photovoltaic effect is

$$\omega_o = \frac{\Delta}{\varepsilon}\left[J_{sb}\beta_b + \frac{qn_s\mu_s}{l_{sub}} \right]$$

where J_{sb} is the theoretically induced substrate current density, β_b is equal to q/nKT, μ_s is the mobility of the substrate material, and n_s is the doping density. The RC time constant may be reduced by as much as an order of magnitude or more by appropriately tailoring the doping profile at the barrier. This can be accomplished so that it will cause no adverse affect on the microwave characteristics of the MMIC.

Improved optical coupling, in combination with reduction of the RC constant of the MESFET is expected to improve its frequency response so that it will equal or better that of the PIN up to 10 GHz. The ramification of this for various optically controlled circuits is vital. One such example, direct optical injection locking of oscillators, is described next.

Optical Injection Locking of MESFET Oscillators

While the direct optical injection locking of microwave oscillators has been explored [9-10], most of the earlier results have shown relatively small locking ranges due to poor optical coupling efficiencies into the active element of the oscillator. Indirect opticalinjection locking, where the modulated optical signal is first detected by a PIN diode and then electrically injected into the oscillator, have yielded better results [11]. Since the PIN diode fabrication is not compatible with commonly used MMIC processing technology, indirect optical injection locking does not lend itself for chip level integration.

The intent of the direct optical injection locking experiments presented here was to demonstrate and quantify how improved optical coupling increases the locking bandwidth. For the present work, two oscillator were designed on Touchstone, one for each of the two MESFETs described above. The design was based on a high impedance transmission line in the gate circuit as to simulate a series inductance which would result in a negative resistance at the drain. The oscillator was fabricated in a gold-on-alumina substrate in microstrip form. Both oscillators were optically injection locked.

A set of background injection locking experiments was carried out, with the experimental setup shown in Fig. 2, to determine the oscillator's external quality factor, Q_{ext}, by use of Adler's equation:

$$\Delta f = \frac{f_{osc}}{Q_{ext}}\sqrt{\frac{P_{inj}}{P_{out}}}$$

where P_{out} is the output power of the oscillator, P_{inj} is the injection locking signal power, f_{osc} is the free running oscillator operating frequency, and Δf is the locking range.

First, under dark conditions, the ITT oscillator was evaluated electrically for output power, free running oscillation frequency, and quality factor, Q. The oscillator had an output power of 5.7 dBm at a frequency of 5.816 GHz, and a locking range of 6.7 MHz was observed. These measurements yielded a Q of 7.5. However, since an optical input to the MESFET changes the operating conditions of the oscillator, the device was illuminated by an unmodulated (dc) light of 4mW from a semiconductor laser, and the electrical characterization was repeated using the test setup shown in the block diagram of Fig. 2. The free running oscillator frequency shifted to 5.813 GHz, the output power was reduced to 0.83 mW, the locking range was 12.9 MHz, and the Q was calculated to be 8.25. The injection locking power for both cases was 1 μW, but the reflection coefficient was 0.85; therefore, the actual power injected to the oscillator was 0.28 μW.

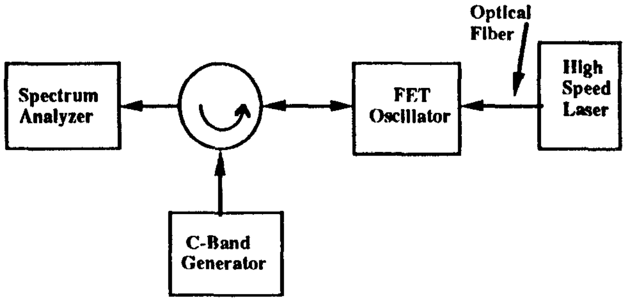

Fig. 2. Block diagram of the test setup for electrical characterization of the free running oscillator.

For the optical injection locking measurements, the microwave signal directly modulated a high speed laser, as shown in the block diagram of Fig. 3. The laser diode was biased to 4mW and modulated with a 10 mW of rf signal. On the basis of the frequency response of the high speed fiberoptic link with the ITT device (Fig. 1), we estimated that the injected optical power to the MESFET is equivalent to about 1 to 3 μW of received rf power at 5.8 GHz. This corresponds well to the injected power levels used in the electrical injection locking experiments. The optical injection experiments resulted in an empirical locking bandwidth of 43.8 MHz, which is an order of magnitude better then previously reported results.

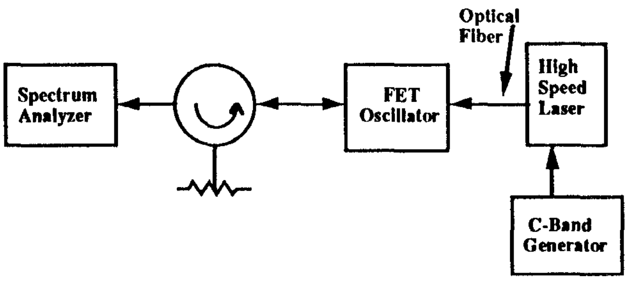

Fig. 3. Block diagram of the test setup for optical characterization of the free running oscillator.

The oscillator with the Fujitsu device device, which has a lower optical coupling efficiency, under indentical experimental conditions gave a locking range of only 7 MHz.

Improving the optical coupling efficiency for the ITT device by the measures discussed earlier would yield a locking range in excess of 100 MHz. This would render direct optical injection locking of local oscillators as an attractive alternative to indirect optical injection locking [11].

Conclusion

This study demonstrates that the optical coupling to a MESFET, when used as and optical detector, is of critical importance. Both the frequency response and injection locking bandwidth can be increased by the careful redesign of the MESFET. These changes can include reducing the drain and source metalization and increasing the number of gate fingers. Furthermore, the RC time constant associated with the internal photovoltaic effect, which currently limits the high frequency performance of the MESFET, may be reduced by as much as an order of magnitude or more by the appropriate tailoring of the doping profile at the barrier (epi-substrate interface). This step would extend the frequency spectrum of the device by an order of magnitude, without adversly affecting either the microwave characteristics of the MMIC or its processing. Improved optical coupling, in combination with reduction of the RC constant of the MESFET, is expected to improve its frequency response so that it will equal or better that of the PIN up to 10 GHz. This approach would provide for chip level integration of optical and microwave functions, such as direct optical injection locking of local oscillators, which have application in fiberoptic feed networks for phased array antennas.

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