MMIC Compatible Lightwave-Microwave Mixing Technique

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Abstract—**The work presented here concerns the mixing of a microwave signal with a modulated optical signal in a MESFET. A brief theoretical analysis of the mixing mechanism is given in terms of the input signal parameters and device characteristics. Experimental results for the IF response of the MESFET as a function of RF frequency, incident optical power, optical modulation depth and gate bias voltage are shown. The IF response and the noise figure of the MESFET below 700 MHz were smaller than those of a p-i-n detector/Schottky mixer combination.**

I. Introduction

The BASIC motivation for the research presented here is the chip-level integration of microwave and photonic components. It is demonstrated that a microwave signal can be mixed with a modulated optical signal in a MESFET, the most commonly used device in MMIC's. Applications include optically addressed microwave circuits, particularly MMIC's, for the up- and down-conversion of microwave signals.

The optical control of hybrid and monolithic microwave devices and circuits has been described by several investigators [1]–[4]. Bhasin *et al.* [5] fabricated and successfully tested a p-i-n diode optical detector on a GaAs MMIC substrate for the optical control of a phase shifter. For many applications such as the optical injection locking of local oscillators or the mixing of a modulated optical signal with a microwave signal, the illumination of an active device is required. For MMIC applications, the MESFET is the most desirable active device since it requires no additional processing steps. An alternate approach, mixing two optical signals to generate a microwave signal, has been studied by Fetterman *et al.* [6].

II. Photoresponse of the MESFET

The following discussion is based on recent work by Madjar and Paolella [7], [8] related to the internal photovoltaic effect in the MESFET, which gives rise to photoresponse in the device. In the internal photovoltaic effect, illustrated in Fig. 1, the absorbed photons modulate the channel-substrate barrier, thereby modulating the channel height. In effect, the light acts as an "optical gate." We take advantage of this effect to mix an optical signal with a microwave signal in the device.

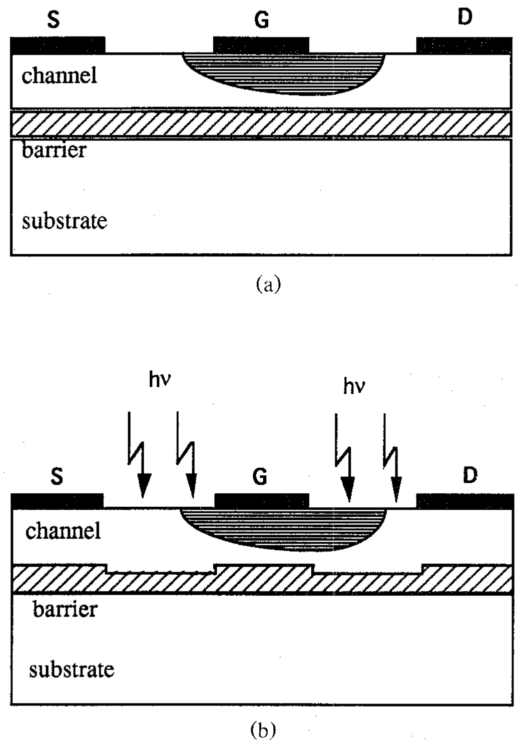

Fig. 1. Internal photovoltaic effect in a GaAs MESFET. The difference in dop-i-ng level between the epi and substrate layers produces a potential barrier in the standard MESFET, as shown in (a). When illuminated, the potential barrier is reduced, as depicted in (b), thereby increasing the channel height (optical gate).

The drain-source current photoresponse for an ITT MESFET was measured as a function of gate-source voltage from 0 to −2.8 V. The optical signal was derived from a double heterojunction structure medium power laser operating at 850 nm. The output of the laser is connected to a fiber with core and cladding diameters of 50 μm and 125 μm, respectively. An optical attenuator controlled the power to the MESFET. The optical signal is routed to the MESFET via a cleaved output fiber positioned over the MESFET.

The measured results are presented in Fig. 2. The drain current photoresponse is determined by the measurement of the drain current in the dark and the drain current under illumination, and is expressed as

$$I_{ph} = I_d(\text{illuminated}) - I_d(\text{dark}). \quad (1)$$

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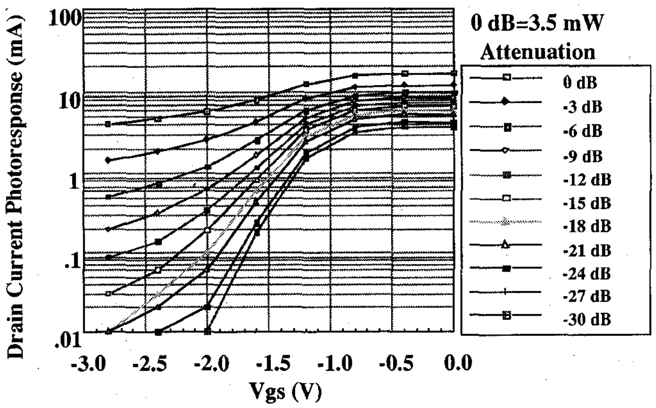

Fig. 2. Drain current photoresponse of the MESFET as a function of gate-source voltage.

The photoresponse of the drain current is due to the internal photovoltaic effect [7] and is given as

$$I_{ph} = g_m V_{ph} \tag{2}$$

where g_m is the transconductance of the device. V_{ph} is the optically induced photovoltage [10], which can be written approximately as

$$V_{ph} \approx c_1(L_o)P + c_1\, p\, (L_o)^{(p-1)}\, (L - L_o) + \cdots \tag{3}$$

where L is the optical intensity, and L_o is the optical intensity at the operation point. The higher power terms are omitted. The coefficients c_1 and p depend on the specific MESFET. To obtain the coefficients, the photovoltage was measured as a function of optical intensity. The measured relationship was approximated using a curve fitting method. As a result the values of the coefficients were $c_1 = 0.3$ and $p = 0.14$.

In Fig. 2 the maximum optical intensity of 3.5 mW is used as the 0 dB reference, and for each successive curve the intensity is attenuated by 3 dB. Under small signal conditions (i. e., low optical powers of -18 dB to -30 dB), the photoresponse follows the transconductance (g_m) of the device, which is essentially constant (40 mmohs) with gate bias from 0 to -0.5 V. The photoresponse is dominated by the product of the internal photovoltage and gm when no external resistance is connected to the gate (i. e., $R_g = 0$). As optical intensity is increased, there are contributions to the photoresponse from the substrate photocurrent and the photoconductive current in the channel [9]. The internal photovoltage which is an exponential function will be large resulting in a significant photoresponse well beyond the p-i-nch-off of -1.6 V.

III. Mixing Mechanism in the MESFET

The mixing effect is the result of the device nonlinearities. In general all elements of the internal equivalent circuit exhibit some nonlinearity, however, the dominating factor is the nonlinearity of the drain-source current versus gate-source voltage characteristics. A small effect is obtained from the nonlinear gate-source capacitance as well.

The drain-source current is expressed as a power series of the gate-source voltage at a constant drain-source voltage

$$I_d = I_{db} + a_1 V_{gl} + a_2(V_{gl})^2 + a_3(V_{gl})^3 + \cdots \tag{4}$$

where a_1, a_2 and a_3 are coefficients that depend on the drain-source voltage, and I_{db} is the dc quiescent point. V_{gl} is the gate-source voltage under illumination.

The effect of illumination on the drain-source current is taken into account by introducing the optically induced photovoltage V_{ph} which is dependent on the light intensity as given by (3). Thus in case of illumination the gate-source voltage is the sum of the electrically applied voltage and the photovoltage

$$V_{gl} = V_g + V_{ph}. \tag{5}$$

The lightwave illuminating the device is modulated:

$$L = L_o[1 + m\cos(\omega_1 t)] \tag{6}$$

where L_o is the average optical intensity, and ω_1 and m are the modulation frequency and depth, respectively.

A microwave signal is simultaneously applied across the gate and source

$$V_g = V_{s0}\cos(\omega_2 t) + V_{gb} \tag{7}$$

where V_{s0} is the amplitude, ω_2 is the angular frequency of the microwave signal, t is the time, and V_{gb} is the biasing gate-source voltage.

Thus the gate-source voltage under optical illumination is the sum of the electrically and optically induced voltages

$$V_{gl} = V_{gb} + V_{ph0}\cos(\omega_1 t) + V_{s0}\cos(\omega_2 t) \tag{8}$$

where V_{ph0} is the amplitude of the photovoltage

$$V_{ph0} = c_1\, p\, m(L_o)P. \tag{9}$$

The mixing product in the drain-source current at the intermediate frequency $\omega_2 - \omega_1$ is obtained by substituting (8) into (4)

$$I_{d\text{mix}} = a_2 V_{ph0} V_{s0}. \tag{10}$$

For this result we assume that the second order nonlinear term of (4) is much larger than the higher order terms (i.e. small-signal case). This simplified theoretical derivation shows the dependence of the mixing product in the drain-source current on all the pertinent parameters of the microwave input V_{s0}, optical input L_o, and m, as well as the device characteristics, a_2, c_1, and p.

The other nonlinearities of the device can also influence the mixing product, however, their contribution is small. Nevertheless, some effect is obtained from the nonlinearity of the gate-source capacitance. The two signals, i.e. the electrically and the optically induced signals are mixed in the nonlinear gate-source capacitance and then they are amplified due to the transconductance of the device. The capacitive mixing product in the drain-source current is expressed as

$$I_{d\text{mix/cap}} = \alpha c_c V_{s0} V_{ph0}/2 \tag{11}$$

where α is a coefficient presenting the part of the optically induced voltage V_{ph} which effects the gate-source capacitance, and $c_c = \partial C_{gs}/\partial V_g$ being the derivative of the gate-source capacitance with respect to the gate-source voltage. The parameter c_c, represent the part of the photovoltage which

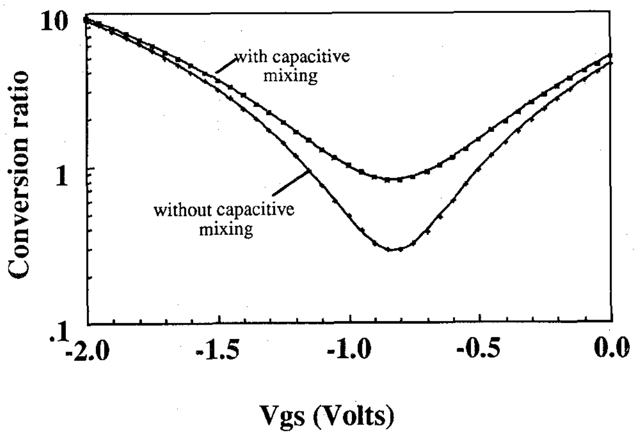

Fig. 3. Conversion ratio as a function of the gate-source voltage with and without capacitive mixing.

influences the gate-to-source capacitance. That influence was measured and a curve fitting method was used to obtain c_c. The parameter α, was estimated based on the construction of the FET used. In our example $\alpha = 0.6$, and $c_c = 0.066$.

The mixing products in the drain-source current are presented in Fig. 3 based on the measurements performed recently to determine the elements of the MESFET under optical illumination [11]. In Fig. 3 the conversion ratio is plotted with and without capacitive mixing as a function of the gate-source voltage. The conversion ratio is defined as

$$Cr = I_{d\text{mix}}/V_{s0}V_{ph0}. \tag{12}$$

As seen in Fig. 3 the contribution of the nonlinear gate-source capacitance is quite small. Some noticeable effect is only observed around the minimum conversion ratio where the drain-source current nonlinearity produces a small mixing product.

IV. Experiments

Two mixing experiments were carried out, which have been called "direct" and "indirect" mixing. In the direct mixing case, we take advantage of the inherent nonlinearities of the MESFET to achieve both detection and down-conversion and amplification of the modulated optical signal. This direct mixing approach is the focus of this paper.

The MESFET, ITT GTC213-1, had four 75-μm-wide gate fingers, a gate length of 0.8 μm and a dopant concentration of 3 $\times 10^{17}$ cm^{-3}. The device was operated with a reverse bias of 0.5 V at the gate and a drain-source voltage of 2 V. For the direct mixing approach, the signal from an 850 nm wavelength laser with an 8 GHz bandwidth was directly modulated by an RF source and conveyed to the MESFET by a multimode optical fiber terminated by a hemispherical lens for enhanced optical coupling. In addition to the optical input, a signal from a second RF source was applied to the gate of the device and the IF output was measured at the drain using a spectrum analyzer with a resolution bandwidth of 100 kHz. As shown by (7), the IF term of the drain current is dependent on the optical modulation depth m. To maximize the IF response, 100% modulation depth was used on the laser, which has an average optical output power of 1.8 mW.

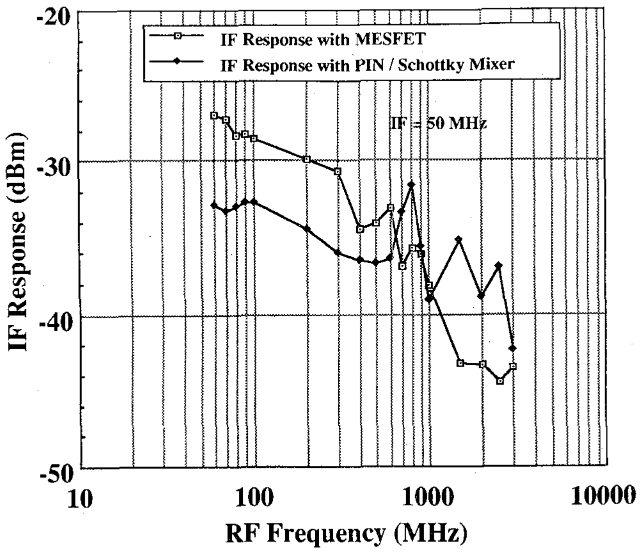

Fig. 4. IF response of the two mixing configurations.

As a baseline for comparison, indirect mixing was also accomplished with a p-i-n photodetector and a Schottky barrier mixer in place of the MESFET to perform the detection and down-conversion functions. The photodetector had a 10-GHz bandwidth, a responsivity of 0.35 mA/mW and a diameter of 25 μm. The p-i-n operated with a reverse bias of 8 V. For the indirect mixing approach, the signal from the laser was again directly modulated by an RF source and detected by the p-i-n photodetector. This detected signal current was mixed with the signal from a second RF source in the mixer (Mini-Circuits ZFM-15) and the IF output was measured at the mixer output. Throughout the experiments both RF sources were set to +5 dBm.

V. Results

The IF response of the two mixer configurations are plotted as a function of the modulation frequency in Fig. 4. The frequency difference between the sources was held constant at 50 MHz. The IF response of the MESFET exceeds that of the p-i-n/Schottky mixer combination up to an RF frequency of about 700 MHz. The MESFET IF response is plotted along with the photoresponse of the device as a function of the RF frequency in Fig. 5. The IF response emulates the photoresponse spectrum of the device with a conversion loss in the range of 7–11 dB. Under the same conditions the Schottky mixer had a conversion loss in the range of 4–10 dB. Clearly, as these results show, the MESFET can be used as mixer with optical and microwave inputs. Depending upon the particular application, the data may be an optical signal and the local oscillator an electrical signal, or vice versa.

The dependence of the IF response of the device on the average incident optical power and the RF drive power to the laser is shown in Fig. 6. The slope of the lines indicates that a 1 dB decrease in optical power incident on the device translates into a 2 dB decrease in the IF response, as expected with square law behavior. The figure also indicates that the IF response decreases linearly with RF drive power to the

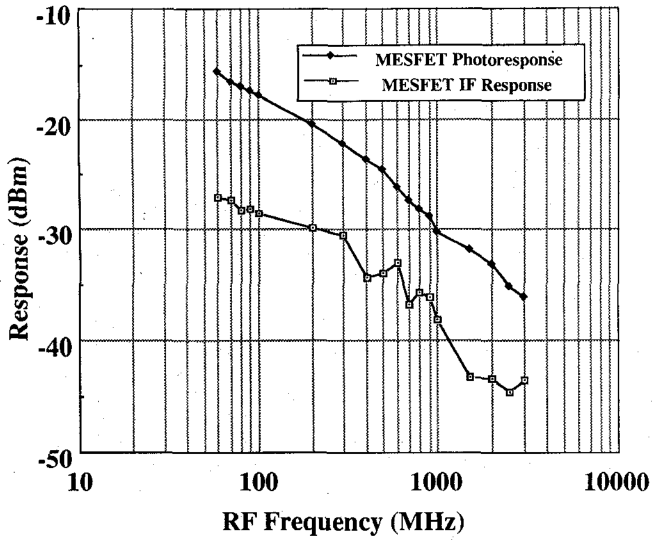

Fig. 5. Photoresponse and IF response of the MESFET.

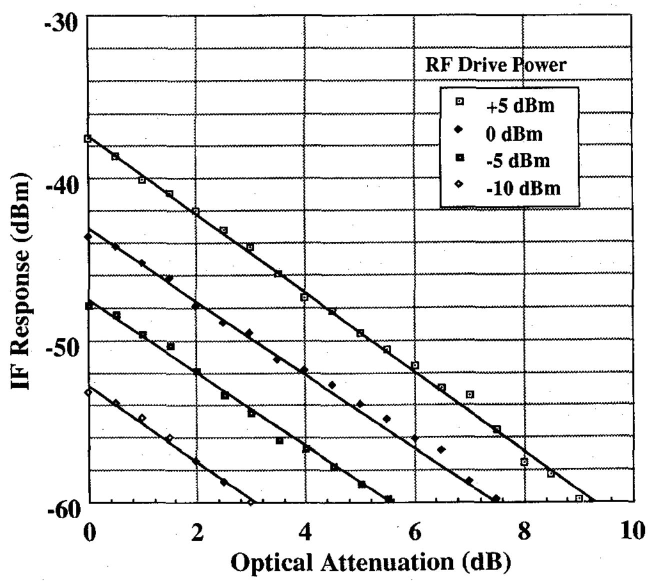

Fig. 6. IF response of the MESFET versus optical attenuation at various RF drive levels. The incedent optical power to the MESFET is 1.8 mW.

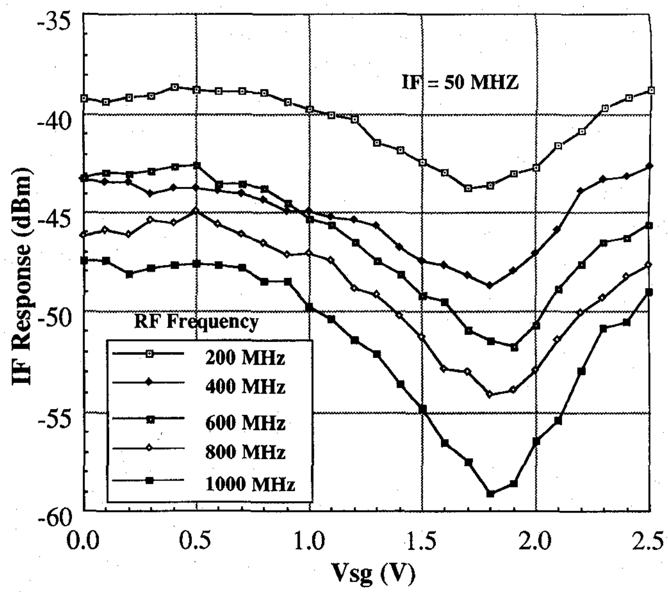

Fig. 7. IF response of the MESFET versus source-gate voltage.

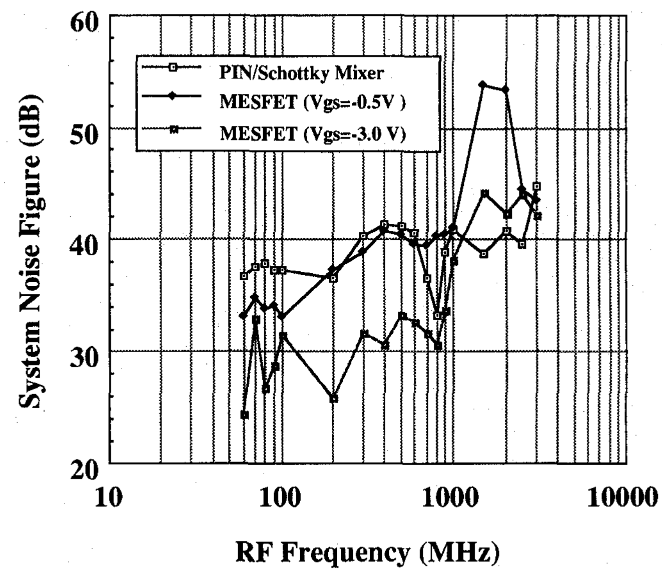

Fig. 8. System noise figure as a function of the RF frequency.

laser (modulation depth). The IF response of the MESFET is also strongly dependent on the gate bias voltage. A plot of the IF versus source-gate voltage at various RF frequencies is shown in Fig. 7. The IF response is maximized when the gate is reverse biased at around 0.5 V, which is also the bias voltage at which the transconductance of the device is maximized. Larger reverse bias voltage on the gate decreases the IF response significantly due to a reduction in the gain. However, at bias voltages larger than 1.8 V the IF response increases again. This is most likely due to the voltage dependence of the nonlinear coefficient a_2.

The system noise figure is presented in Fig. 8 as a function of the RF frequency. In the figure 3 curves are plotted: one for the p-i-n/Schottky mixer configuration and two for the MESFET with different bias voltages. The noise is significantly smaller with a bias voltage close to p-i-nch-off because then the drain-source current is also smaller. As seen the system noise figure below 1000 MHz is smaller in the case of the MESFET than with the p-i-n/Schottky mixer configuration if a bias voltage close to p-i-nch-off is used. However, the system noise figure above 1000 MHz is higher in the case of the MESFET compared to the p-i-n/Schottky mixer configuration.

VI. Discussion

In order to enhance the performance of the MESFET in the direct mixing configuration two issues must be addressed: how to improve the photoresponse of the MESFET, particularly at higher frequencies, and how to improve the mixing process itself. To improve the high frequency response of the MESFET, several steps can be taken. The optical coupling efficiency, the fraction of the absorbed to incident photons, is less than 10% for the MESFET since the metal electrodes block most of the light from entering the GaAs. By altering the geometry of the device (shorter but larger number of gate fingers), by providing an elliptical spot size (cylindrical lens), and by an antireflection coating on top of the MESFET, the optical coupling efficiency could be enhanced to 40% or higher. This corresponds to a 12 dB increase in the photoresponse (and in the IF output) of the MESFET in the entire spectral range.

Further optimization in the frequency response of the MESFET can be achieved by modifying the dop-i-ng profile and by increasing the dop-i-ng ratio between the epi layer and the substrate to decrease the barrier capacitance. This would reduce the RC time constant associated with the internal photovoltaic effect which dominates the photoresponse.

VII. Conclusion

The work presented here concerned the mixing of a microwave signal with a modulated optical signal in a MESFET. A brief theoretical analysis of the mixing mechanism was given in terms of the input signal parameters and device characteristics. Experimental results for the IF response of the MESFET as a function of RF frequency, incident optical power, optical modulation depth and gate bias voltage were presented. The IF response and the noise figure of the MESFET below 700 MHz were smaller than those of a p-i-n detector/Schottky mixer combination.

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