MMIC Compatible Lightwave-Microwave Mixing Techniques

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Abstract

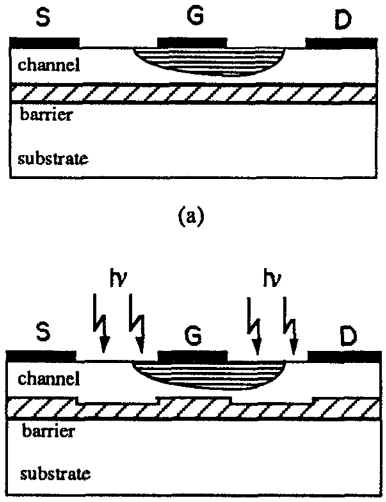
The work presented in this paper concerns the mixing of a microwave signal with a modulated optical signal in a MESFET. A brief theoretical analysis of the IF term of the drain current is given in terms of the input signal parameters and device characteristics. Experimental results for two mixing configurations using the MESFET are shown, along with biasing conditions which maximize the IF response.

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 MMICs. Applications include optically addressed microwave circuits, particularly MMICs, for the up and down conversion of microwave signals.

The optical control of hybrid and monolithic microwave circuits, such as switches, attenuators, phase shifters and mixers, has been described by several investigators[1-4]. Bhasin *et al*[5] fabricated and successfully tested a PIN diode optical detector on a GaAs MMIC substrate for the optical control of a phase shifter. However, 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 direct 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].

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 epi-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.



(b)

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

Theory

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

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$$I_{ds} = g_m V_{ph} \quad (1)$$

where g_m is the transconductance of the device. Vph is the optically induced photovoltage[9], which can be written approximately as:

$$V_{ph} \approx c_1(Lo)^p + c_1(Lo)^{(p-1)}(L - Lo) + ... \quad (2)$$

where $L = Lo[1 + m\cos(\omega_1 t)]$ is the modulated optical intensity, Lo is the average optical intensity, and ω_1 and m are the modulation frequency and depth respectively. The coefficients c_1 and p depend on the specific MESFET. The voltage at the gate, V_g, due to the microwave signal, V_s, with frequency ω_2, is

$$V_g = V_s \cos(\omega_2 t) \quad (3)$$

The drain current, at a given bias level, can be written as

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

where a_1, a_2 and a_3 are coefficients that depend on the bias voltages, and I_{db} is the d.c. quiescent point. The sum of the electrically and optically generated voltages, V_{gl}, is

$$V_{gl} = V_g + V_{ph} \quad (5)$$

Substituting eq. 5 into eq. 4 yields the component of the drain current at the intermediate frequency $\omega_2 - \omega_1$:

$$I_{d(IF)} = c_1 a_2 p m (Lo)^p V_s \quad (6)$$

This simplified theoretical derivation shows all the dependence of the IF term of the drain current on all the pertinent parameters of the microwave input Vs, optical input Lo, m, and the device characteristics, a_2, c_1 and p.

Experimental Setup

Two basic experimentations were carried out, "direct" and "indirect" mixing, as shown in Figs. 2 and 3. In an indirect mixing configuration (Fig.3), the MESFET serves as a detector for the optical signal and the down-conversion is performed in a conventional Schottky barrier mixer. However, by taking advantage of the inherent nonlinearities of the MESFET, both detection and down-conversion of the modulated optical signal can be achieved in the device. This direct mixing approach, shown in Fig.2, is the focus of this paper.

The signal from an 850 nm wavelength Ortel SL 1020 laser, directly modulated by RF Source 1, was conveyed to the MESFET by a multimode optical fiber terminated by a hemispherical lens for enhanced optical coupling. A three-axis computer controlled micropositioner was used to position the fiber for maximum photoresponse. 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 x 10^{17} cm^{-3}.

The device was operated with a reverse bias of 0.5 volt at the gate and a drain-to-source voltage of 2 volts. Throughout the experiments RF Source 1 and RF Source 2 amplitudes were set to +5 dBm. As shown by eq. 6, 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 Ortel laser, which has an average optical output power of 1.8 mW.

For the direct mixing configuration, in addition to the optical input, a signal from RF Source 2 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.

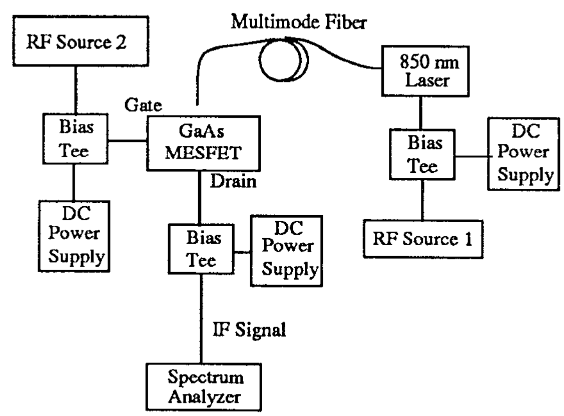

Fig. 2. Direct mixing configuration.

For the indirect mixing configuration, shown in Fig. 3, the MESFET was used as an optical detector. The detected signal from the MESFET was mixed with the signal from RF Source 2 in a Mini-Circuits ZFM-15 mixer. As a baseline for comparison, indirect mixing was also accomplished with a PIN photodetector in place of the MESFET. The photodetector was an Ortel PDO25-PM operated with a reverse bias of 8 volts.

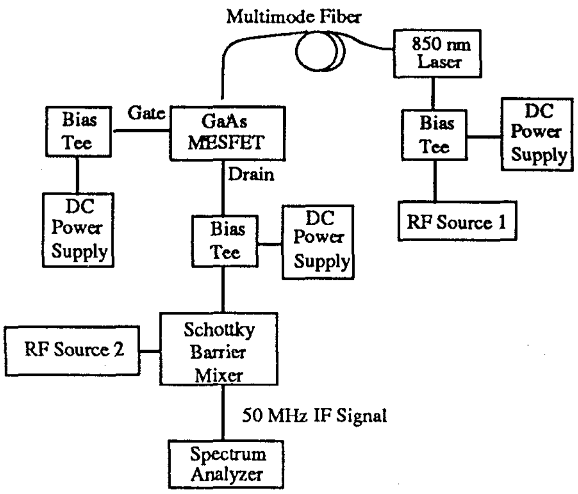

Fig. 3 Indirect mixing configuration

The IF response of the three mixer configurations, as well as the photoresponse of the MESFET, are plotted as a function of the modulation frequency in Fig.4. The frequency difference between the sources was held constant at 50 MHz.

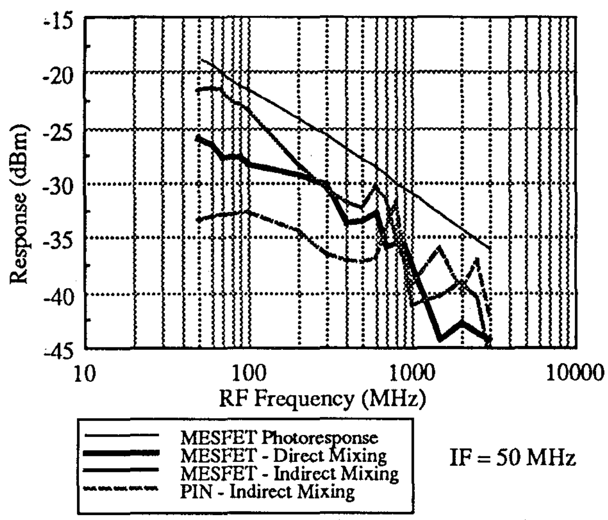

Fig.4. Response of the MESFET and the down-converted IF as a function of RF frequency for three different configurations, as discussed above.

The IF response of the MESFET is strongly dependent on the gate bias voltage. A plot of the IF response vs. source-gate voltage is shown in Fig. 5. The IF response is maximized when the gate is reverse biased at around 0.5 V.

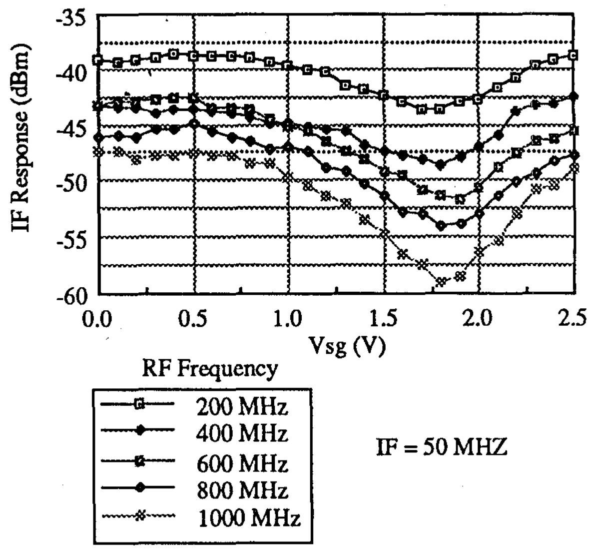

Fig. 5 IF response vs. source-gate voltage

Discussion

In general terms, the down-converted IF output of the MESFET in the direct configuration emulates the photoresponse spectrum of the device with a conversion loss in the range of 5 to 10 dB. The experimental results depicted in Fig.4 were carried out with no impedance matching at the inputs and the outputs, which accounts for the peaks and valleys in the spectra. 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.

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 into 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 doping profile and by increasing the doping ratio between the epi layer and the substrate to reduce the barrier capacitance. This would reduce the RC time constant associated with the internal photovoltaic effect or optical gate and extend the corner frequency by a decade.

In this investigation, an optimum gate-source voltage was found to maximize the level of the mixing product. However, the noise figure of the MESFET is also dependent on gate-source voltage, and the optimum noise figure may occur at a gate-source voltage which differs from that of the maximum IF response.

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