DYNAMIC CHARACTERIZATION OF OPTICAL-MICROWAVE TRANSDUCERS

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ABSTRACT

Optical-microwave transducers applying FET devices are investigated to determine their dynamic characteristics. It is observed that the result of the well known frequency response method is differing from the result of a combined test method applying simultaneously a microwave signal and a modulated lightwave for driving the transducer. Based on these investigations a more precise circuit model is established for illuminated FET devices. The new circuit model is well applicable to describe the operation of optical-microwave transducers like mixers, phase detectors, amplifiers, injection locked oscillators, modulators.

INTRODUCTION

The optical-microwave transducers are usually characterized by means of intensity modulated lightwaves. The lightwave has an analog or digital modulation. In the analog case the frequency response is the main tool to describe the dynamic behavior. In the digital case the distortion of the modulation pulses is the right characteristic. These methods are well applicable for photodetectors. However, for more complex circuits a more sophisticated characterization is needed according to our recent investigations.

Therefore, measurements are performed on combined optical-microwave transducers containing FET devices. It is observed that the result of the frequency response method is differing from the result of the combined test method applying simultaneously a microwave signal and a modulated lightwave for driving the circuit. Based on these investigations a more precise circuit model is established.

INVESTIGATIONS

Measurements are carried out on a microwave circuit containing a FET device as the active element. For illumination a GaAs/GaAlAs laser diode is used providing 1 mW optical output power at a wavelength of 780 nm. The laser beam is focussed by two lenses to produce a light spot with a diameter of approximately 100 μm. The reflectance of the device surface is checked by tilted beam. The result is rather good: the reflected beam intensity is only 45 % of the incident beam. That figure includes the reflection from the metal surfaces of the electrodes as well.

Frequency response

First the frequency response is measured. The device is illuminated by a laser beam carrying intensity modulation. The average incident optical power is 1 mW and the optical modulation depth is approximately 2 %. The detected output power is measured varying the modulation frequency. The result is shown in Fig. 1.

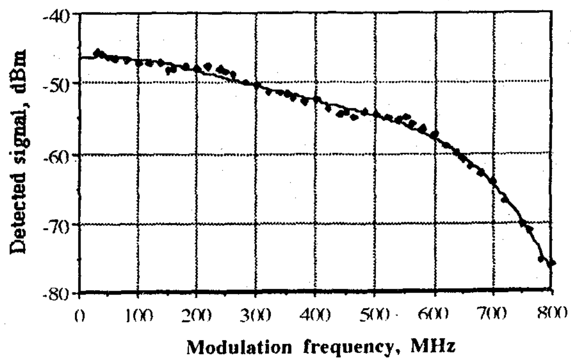

Fig. 1 The detected signal versus the modulation frequency

The detected signal exhibits a decay with increasing modulation frequency. The decay is relatively slow at low modulation frequencies. The measurement result is in accordance with the recently published theoretical and experimental investigations [1,2]. According to these investigations the decrease in the detected signal with increasing modulation frequency is due to the time constant of the barrier depletion region between the substrate and the epitaxial layer.

The detection process is strongly influenced by the bias conditions. Fig. 2 shows the detected signal as a function of the gate-source voltage. The drain-source voltage is 3 V. The modulation signal level is 0 dBm, and its frequency is 50 MHz. The average optical power is 1 mW. As seen in Fig. 2 the detected signal is almost zero at the pinch-off voltage, then it is increasing with decreasing the magnitude of the gate-source voltage and finally reaches an almost constant value.

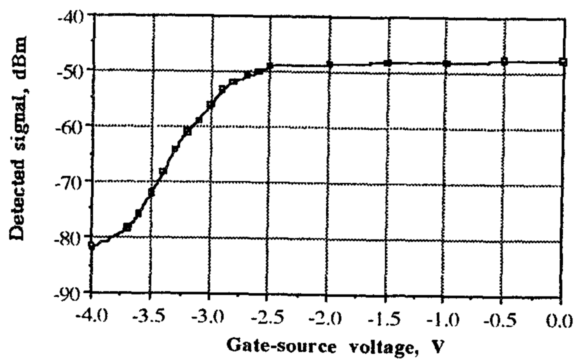

Fig. 2 The detected signal as a function of the gate-source voltage

The dependence of the detected optical signal on the bias voltage can be explained utilizing the concept of the photo-response [2]. In this approach the additional current generated by the absorbed photons is responsible for the detection process. The photo-response is small at the pinch-off voltage, then it increases and reaches a constant level when the magnitude of the gate-source voltage is increased. That is in accordance with the relationship of the detected signal as a function of the gate-source voltage.

The next question is whether the dynamic properties in the detection mode and in the conversion mode of operation are the same.

Converted response

Optical-microwave conversion investigations were already performed [3-7]. These experiments provided significant knowledge although some questions remained open: first of all the dynamic characteristics which are very important in many applications when the light is intensity modulated by a high frequency or high bit rate signal.

In the next test both the optical and microwave gates are driven by signals. Between the gate and source a 2 GHz microwave signal is applied while the intensity modulated signal of a semiconductor laser diode is used to illuminate the active device. This way an alternative of the frequency response is measured i.e. instead of the detected signal the converted signal is used as a proper characteristic. The converted response is presented in Fig. 3 by the first sideband. The frequency dependence is now different, the decay in the converted response is much higher at low modulation frequencies, and it is more pronounced with increasing modulation frequency compared to the frequency response of the detected signal. That is also seen from the curve of the second sideband.

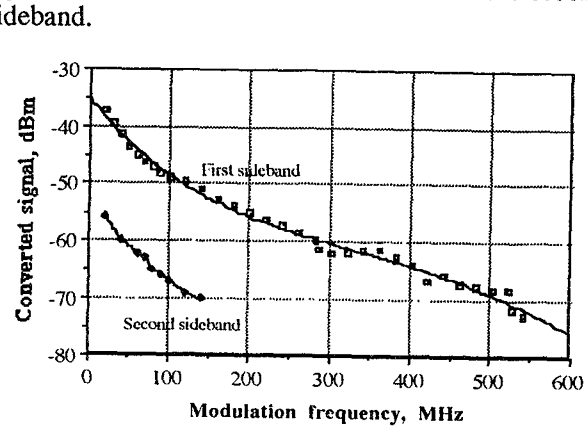

Fig. 3 The converted signal versus the modulation frequency

Now the gate-source voltage is varied to observe its effect on the conversion. Fig. 4 shows the converted signal as a function of the gate-source voltage. The parameter of the curves is the modulation frequency. The drain-source voltage is 4V. The

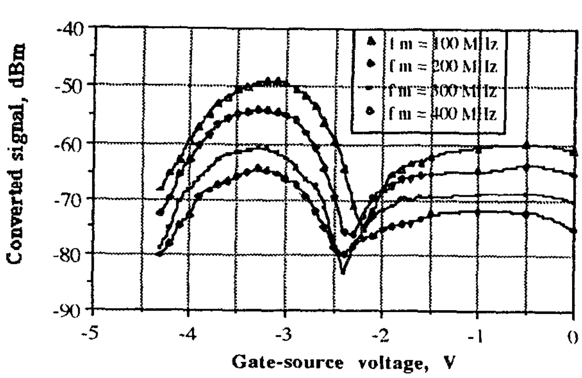

Fig. 4 The converted signal as a function of the gate-source voltage

frequency of the microwave input signal is 2 GHz and its power is 0 dBm. The optical modulation depth is approximately 2%. As seen the converted signal is strongly dependent on the gate-source voltage. At low gate-source voltages the converted signal is minimum, however, close to the pinch-off voltage it exhibits a maximum. This relationship is completely different from that of the detection process when the maximum is obtained at small gate-source voltages.

Comparing the two characterization methods, the frequency response and the converted response along with their dynamic properties, a significant discrepancy is observed. The decay in the converted signal is higher - mainly at low frequencies - than in the detected signal. Another significant deviation is that the decrease in the converted signal is proportional to the modulation frequency, however, the decrease in the detected signal is developed slowly when the modulation frequency is increasing.

NEW CIRCUIT MODEL

The description of the optical effect is based on the physical processes in the device. It is discussed in detail now. The schematic cross section of the device is shown in Fig. 5. An intensity modulated laser beam is used to illuminate the device. One part of the beam is reflected, however, the other part is penetrating into the semiconductor material of the device. Due to the optical absorption charge carriers are generated. Each absorbed photon generates an electron-hole pair. There are two depletion regions: one below the gate and another between the substrate and the epitaxial layer. In the depletion regions the generated charge carriers are drifted because of the applied electric field. In the depletion region between the substrate and the epitaxial layer the electric field is low and the resistivity of the material is high, therefore the drift of the charge carriers is slow which reduces the opto-electric effect at higher frequencies. That is represented by a time constant τ_b [1].

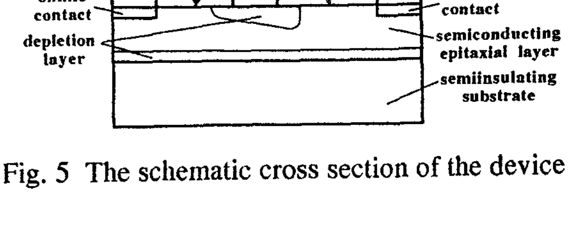

Fig. 5 The schematic cross section of the device

Considering the discrepancy between the responses of the detected and the converted signals, a new circuit model is established. That is presented in Fig. 6. In the circuit model there are two new elements describing the effect of illumination. The voltage source V_{lg} appearing in series with the gate-source capacitance represents the photo-detection between the gate and source of the device. The other new element is a parametric transconductance. That shows the effect of illumination on the conductive channel of the device. Due to the charge carrier generation the extension of the depletion regions is reduced by the illumination and thus the height of the conductive channel is increased resulting in a change of the transconductance. Thus the effect of illumination is described by a parametric transconductance which is controlled by the intensity of the optical wave [8]. The parametric transconductance involves the time constant τ_b as well and that is represented by a parallel connected current source, capacitance and conductance. The further circuit elements of the internal device are also functions of the illuminating light intensity [9], however, their effect on the conversion is small [5]. The new circuit model is well applicable to describe the operation of optical-microwave transducers like mixers, phase detectors, injection locked oscillators, modulators, etc.

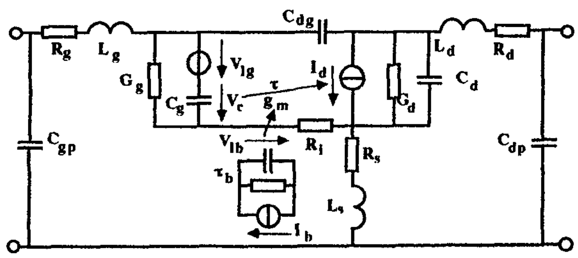

Fig. 6 The new circuit model

To check the applicability of the new circuit model an up-conversion test is carried out as an example. First the d.c. drain-source current of the FET device is measured as a function of the gate-source voltage with and without illumination. From the measured data the transconductance is derived. Then the gate-source current is measured which describes the effect of illumination between the gate and source of the device. From these experimental data the parametric transconductance and the voltage source V_{lg} are determined. Having known these values the static converted signal is calculated. That is plotted in Fig 7 as a function of the gate-source voltage.

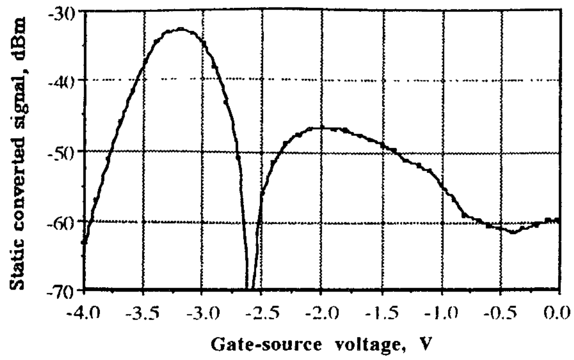

Fig 7 The static converted signal as a function of the gate-source voltage

To compare the calculated curve with the experimental results, measurements are performed at low modulation frequencies as well. The circuit is driven by a 2 GHz microwave signal and it is simultaneously illuminated by a laser beam carrying intensity modulation. The frequency of the modulation is varied between 20 and 200 MHz. The result is plotted in Fig. 8. Here the up-converted signal power is shown as a function of the gate-source voltage. The parameter of the curves is the modulation frequency. As seen in Figs. 7 and 8, the shape of the calculated and measured curves are very similar and the maximum is at the same gate-source voltage. However, the level of the up-converted signal is significantly decreased with increasing modulation frequency.

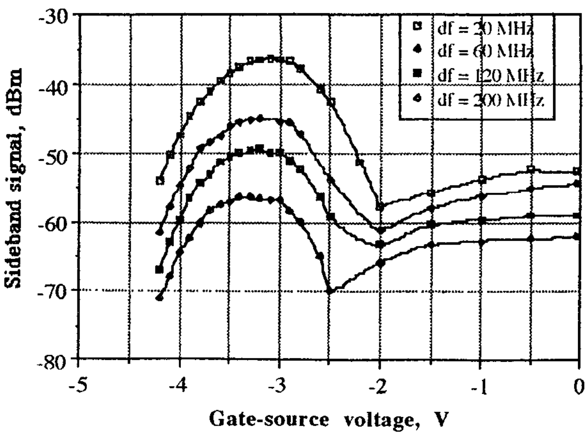

Fig. 8 The up-converted signal as a function of the gate-source voltage

ACKNOWLEDGMENT

The author acknowledges the Commission of the European Communities for supporting the research in the framework of the PECO program. He is also thankful for the support given by the Hungarian National Scientific Research Foundation OTKA.

CONCLUSIONS

Optical-microwave transducers applying FET devices were investigated to determine their dynamic characteristics. It was observed that the result of the well known frequency response method is differing from the result of a combined test method applying simultaneously a microwave signal and a modulated lightwave. Based on these investigations a more precise circuit model has been established for illuminated FET devices. The new circuit model is well applicable to describe the operation of optical-microwave transducers like mixers, phase detectors, amplifiers, injection locked oscillators, modulators.

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