Dynamic Properties of Optical-Microwave Mixing Processes Utilizing FET Devices

Tibor Berceli, *Fellow, IEEE*

Abstract—**The dynamic behavior of the optical-microwave mixing process is investigated in detail. First, the dynamic properties of mixing and detection are compared. With increasing optical modulation frequency a more remarkable decay is obtained in the mixing product than in the detected signal. Based on the investigations there is a further reason for the decay in the mixing product beside the time constant exhibited by the barrier depletion region: the optically induced substrate current which doesn't contribute to the mixing effect. To describe the operation of combined optical-microwave mixing effects a new approach, the parametric method is introduced which provides a better description for these processes.**

I. INTRODUCTION

THE aim of the present paper is to investigate the dynamic properties of optical-microwave mixing and to determine the relationships governing these processes. For that purpose experiments are carried out. Based on their results a new approach is presented to describe the effect of interaction in the semiconductor device under simultaneous optical and microwave drive.

Optical-microwave mixing experiments have already been performed to disclose the behavior of that type of interaction and to determine its properties [1]–[3]. The experiments provided significant knowledge on these problems although some questions remained without the right answer. The strong frequency dependence of optical-microwave mixing has already been observed [4], [5], however, its reason was not investigated in detail yet. Nevertheless, the dynamic properties are very important in many applications when the light is intensity modulated by a high frequency or high bit rate signal. This paper will try to fill this gap up presenting new experimental results on and description methods for the dynamics of optical-microwave mixing processes.

The dynamic behavior of the FET device as an optical detector has already been investigated both theoretically and experimentally [6], [7]. The main result of that investigation is the time constant attributed to the barrier between the substrate and the epitaxial layer. That time constant is considered during our mixing tests as well. However, it can not be used for the proper characterization of the dynamic effects involved in the mixing process. Therefore, measurements are performed on FET devices when they are driven by a microwave signal and simultaneously illuminated by an intensity modulated laser beam.

According to the measurement results, the frequency dependence is different in the case of mixing and detection. With increasing modulation frequency the mixing product is first strongly decreased, then its decrease is reduced. The frequency dependence in the range where the reduced decay is observed, can be justified by the time constant of the barrier. However, the first, more pronounced decay should be the result of another effect as it is explained in this paper.

Understanding the optical-microwave mixing process offers new solutions for many applications, e.g., in subcarrier multiplexed optical communications [8], [9].

Manuscript received January 13, 1995; revised April 4, 1995 This work was supported by the US—Hungarian Joint Fund and the Hungarian National Scientific Research Foundation (OTKA) under contracts T 000118/91 and T 014300/94.

The author is with the Technical University of Budapest, Telecommunications Innovations Ltd., 1111 Budapest, Goldmann György-tér 3, Hungary.

IEEE Log Number 9413691.

II. METHOD OF INVESTIGATION

In the well known approach the effect of illumination is represented by the photo-voltage appearing across the gate-source capacitance [6], [10]. This method is well applicable to describe the static characteristics and the quasistatic behavior of the device. For example, the low frequency photo-detection follows the predicted performance using the photo-voltage concept. The dynamic property of the photo-detection is represented by a time constant reducing the detected signal with increasing modulation frequency [6].

In this paper another approach is presented. That is called the parametric method. It is based on the effect that the amplification of a FET device is modified by the light intensity illuminating it [11]. The amplifier is considered as a black box characterized by the scattering parameters. The main interest is in the transfer characteristics that means in the S_{21} scattering parameter because the input and output are matched to 50 Ohm transmission lines in a wide frequency range. The effect of the optical signal is considered as a perturbation and is described by the parametric variation of the S_{21} scattering parameter.

III. OPTICAL-MICROWAVE MIXING MEASUREMENTS

The combined optical-microwave mixing process is now investigated experimentally. The investigations are carried out on a microwave amplifier-mixer containing a FET device which is illuminated by an intensity modulated lightwave. The microwave amplifier-mixer is developed utilizing a FET device type HP 1101 which is opened to get the light in. The material of the device is GaAs therefore an optical wavelength of 780 nm is used to illuminate its active region. The laser

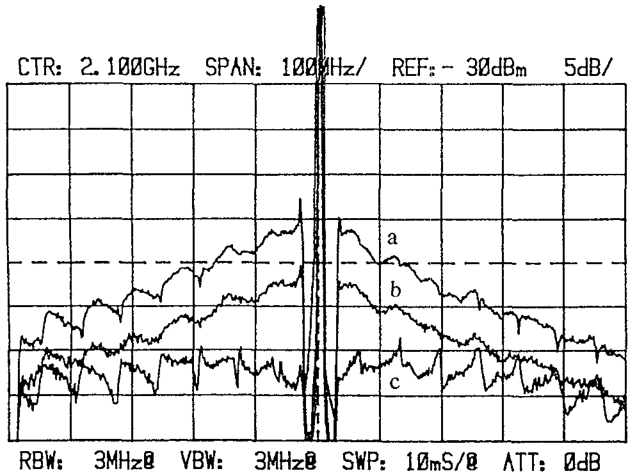

Fig. 1. Mixing product as a function of the modulation frequency. The parameter is the gate-source voltage V_{gs}. (a) $V_{gs} = -3.5$ V, (b) $V_{gs} = -4.0$ V, and (c) $V_{gs} = -1.5$ V.

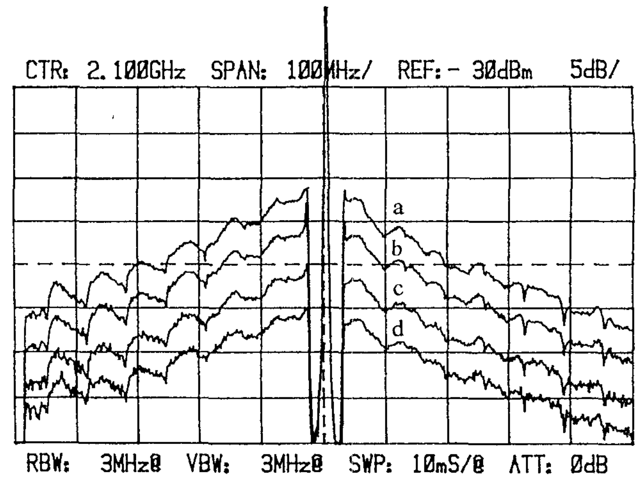

Fig. 2. The mixing product as a function of the modulation frequency. The parameter of the curves is the modulation signal level of the driving circuit P_m: (a) $P_m = 5$ dBm, (b) $P_m = 0$ dBm, (c) $P_m = -5$ dBm, and (d) $P_m = -10$ dBm.

beam is intensity modulated, the modulation frequency is swept in a wide range. The laser beam is focused by two lenses to produce a light spot with a diameter of approximately 100 μm. The microwave input signal has a frequency of 2.1 GHz, and a power level of 0 dBm. The average light intensity is 1 mW. The drain-source voltage is 3 V.

In Fig. 1 the mixing product is plotted versus the modulation frequency which is varied from 30 MHz to 500 MHz. The parameter of the curves is the gate-source voltage: it is -3.5 V for curve a, -4.0 V for curve b, and -1.5 V for curve c. The input power of the laser driving circuit is 0 dBm. Thus the optical modulation depth is approximately 3%. The maximum of the mixing product is obtained close to the pinch-off voltage. However, the mixing product is significantly decreased with increasing modulation frequency. The decay is rather high, and it is a function of the bias as well. At -1.5 V gate-source voltage the decay is much less than close to the pinch-off voltage.

Investigations are carried out to test the effect of the driving level as well. In Fig. 2 the effect of the modulation signal level is shown. The mixing product is plotted versus the modulation frequency. The parameter is now the modulation signal level at the input of the laser driving circuit: it is 5 dBm for curve a, 0 dBm for curve b, -5 dBm for curve c, and -10 dBm for curve d. As seen the shape of the each curve is the same. Thus the dynamic behavior of the mixing process is not dependent on the optical modulation depth which is proportional to the modulation signal level.

Further investigations have also been carried out to test the effect of the microwave signal level. According to these measurements the dynamic behavior of the mixing process is not dependent on this level.

IV. Comparison of Detection and Mixing by FET Devices

The optical detection by FET devices has already been investigated involving its frequency dependence [6], [12]. According to this investigation there is a decrease in the detected signal with increasing modulation frequency and this effect is due to the time constant of the barrier depletion region between the substrate and the epitaxial layer. However, there is a question whether the dynamic properties in the detection and mixing modes are the same. For that purpose measurements were performed on the same circuit in the optical detection mode, too. The comparison is carried out based on these results.

Comparing the dynamic properties of the detection and mixing processes a significant discrepancy is observed. The decay in the mixing product is higher—mainly at low frequencies—than in the detected signal. Another significant deviation is that the decrease in the mixing product is proportional to the modulation frequency even at low frequencies, however, the decrease in the detected signal is developed slowly, step-by-step when the modulation frequency is increasing.

The comparison is based on the physical processes in the device under illumination. In the detection mode of operation the optically generated charge carriers are contributing to the detected electric current in both depletion regions below the gate and between the substrate and the epitaxial layer by changing the height of the conductive channel. Beside that effect the charge carriers generated in the substrate are also participating in the detected current. Therefore, the frequency dependence of the detected signal is determined by the conductive channel current and the substrate current.

On the other side, in the mixing mode of operation the contribution of the substrate current in the generation of the mixing product is negligible because in the substrate there is neither a nonlinear nor a parametric effect. The mixing products are created mainly in the conductive channel. This way their power level is somewhat lower and their frequency dependence is higher [4], [5]. There are two reasons for it: the time constant exhibited by the depletion region between the substrate and the epitaxial layer and the optically induced substrate current which is increasing with the modulation frequency and doesn't contribute to the mixing effect.

V. Parametric Description of the Optical Effect

To describe the combined optical-microwave mixing process introduced. That means the transfer function of the circuit is dependent on the light intensity [11], [13]–[15]. According to that approach the output wave b_2 is given by the product of the input wave a_1 and the S_{21} scattering parameter

$$b_2 = S_{21} a_1. \tag{1}$$

The mixing process can be considered as a perturbation because the optical modulation depth is usually small. Therefore, in the further calculations S_{210} the scattering parameter at the average light intensity is used along with its perturbation caused by the variation of the light intensity

$$S_{21} = S_{210}[1 + \beta(P_{L0})(P_L - P_{L0})]. \tag{2}$$

The S_{21} scattering parameter is proportional to the transconductance. It has already been demonstrated that the effect of illumination on the transconductance follows a logarithmic relationship [14]. That is valid for the S_{21} scattering parameter as well

$$\frac{S_{21} - S_{21d}}{S_{21d}} = \gamma \lg(1 + P_L/P_{Lr}). \tag{3}$$

S_{21d} is the scattering parameter in the dark case, P_L is light power, P_{Lr} is the reference light power, and γ is a coefficient. S_{21d} and γ are dependent on the bias voltages.

Now $\beta(P_{L0})$ is determined based on the logarithmic relationship

$$\beta(P_{L0}) = 0.4343 \frac{S_{21} - S_{21d}}{S_{21d}} \frac{1}{P_{L0} + P_{Lr}} \cdot \frac{1}{\lg(1 + P_L/P_{Lr})}. \tag{4}$$

The input wave has a sinusoidal time function $a_1 = a_{10}\cos(\omega_s t)$ where a_{10} is the input wave amplitude, ω_s is the angular frequency of the input wave, and t is the time.

The incident optical beam is also intensity modulated by a sinusoidal time function $P_L - P_{L0} = mP_{L0}\cos(\omega_m t)$. Here P_{L0} is the average optical power, m is the optical modulation depth, and ω_m is the angular frequency of the modulation signal.

Thus the output wave is obtained as

$$b_2 = S_{21}a_{10}\cos(\omega_s t) + S_{21} m a_{10} \cdot \frac{0.4343}{\lg(1 + P_L/P_{Lr})} \frac{P_{L0}}{P_{L0} + P_{Lr}} \frac{S_{21} - S_{21d}}{S_{21d}} \cdot \cos(\omega_s \pm \omega_m t). \tag{5}$$

VI. Experimental Verification of the New Approach

The scattering parameters S_{21} and S_{21d} are also determined by measurements on the circuit. The average light power $P_{L0} = 1$ mW and the reference light power $P_{Lr} = 1$ μW.

As it has already been seen from the previous mixing measurements there is a significant decay in the power level of the mixing product when the optical modulation frequency is increased. To consider this effect a dynamic transfer coefficient $|H(j\omega_m)|$ is introduced into the equation providing the mixing product

$$b_{20mix} = 0.072 S_{21} m a_{10} \frac{S_{21} - S_{21d}}{S_{21d}} |H(j\omega_m)| \tag{6}$$

where b_{20mix} is the wave amplitude of the mixing product at the angular frequencies of $\omega_s \pm \omega_m$. The above values of P_{L0} and P_{Lr} have already been substituted.

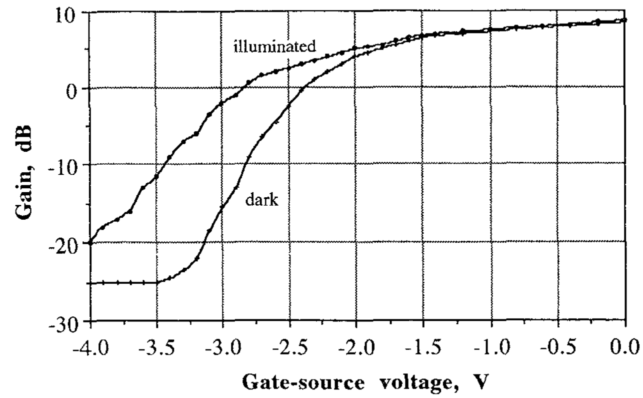

Fig. 3. Measured power gain versus the gate-source voltage.

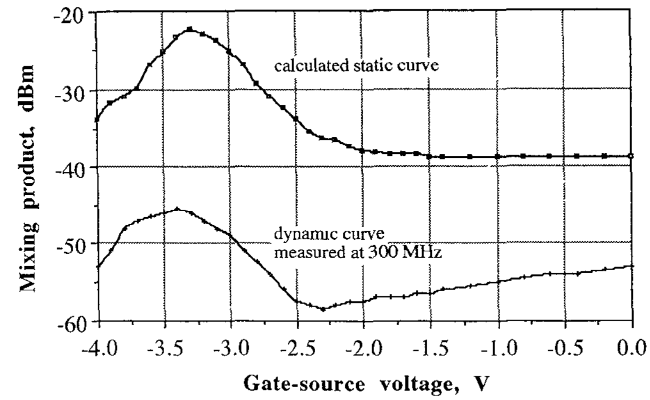

Fig. 4. Static and dynamic mixing products versus the gate-source voltage.

Fig. 3 shows the measured power gain (which is proportional to the square of the transfer scattering parameter, $|S_{21}|^2$) versus the gate-source voltage at the microwave frequency of 2.1 GHz. The lower curve refers to the dark case, and the upper curve is valid when the device is illuminated by a light intensity of 1 mW. The input level of the microwave signal is 0 dBm. The drain-source voltage is 3 V.

Based on these measurement results the static (or low frequency) mixing product is calculated using (5) without applying the dynamic transfer coefficient $|H(j\omega_m)|$. The result is presented by the upper curve of Fig. 4 as a function of the gate-source voltage. The lower curve in Fig. 4 shows the measured dynamic mixing product at a modulation frequency of 300 MHz again as a function of the gate-source voltage. The shape of the curves is very similar. The maximum is obtained at the same gate-source voltage.

However, there is a big difference in the level of the calculated static and the measured dynamic mixing products. The reason is that the dynamic transfer coefficient $|H(j\omega_m)|$ was not considered yet. To determine $|H(j\omega_m)|$

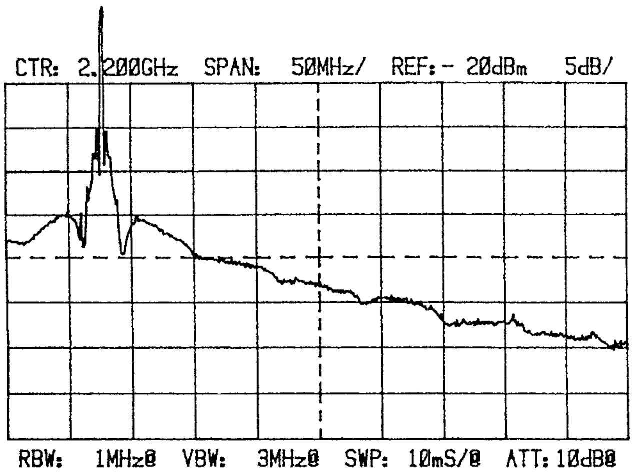

Fig. 5. Mixing product measured as a function of the modulation frequency including the close vicinity of the carrier.

further measurements are done in a range of the modulation frequency including the close vicinity of the carrier as well. The modulation frequency is now varied from 2 MHz to 425 MHz. The result is plotted in Fig. 5 with a gate-source voltage of -3.3 V providing maximum static mixing product. The input power of the laser driving circuit is 0 dBm, thus the optical modulation depth is approximately 3%. As seen the level of the mixing product near the carrier is -25 dBm which is in a good agreement with the calculated static value. Further the decay at 300 MHz is 22 dB compared to the previous level. That is exactly the difference between the two curves in Fig. 4. Thus, $|H(j\omega_m)|^2$ is obtained from Fig. 5 as the power level difference of the mixing product at the specific modulation frequency and very close to the carrier. (The resonant decay around 20 MHz should be avoided.)

Looking at the two curves in Fig. 4 another smaller deviation between the static and dynamic curves is also observed. That is the difference in the shape of the curves approaching the zero gate-source voltage. The reason is that the decay in the mixing product is dependent not only on the modulation frequency but also on the gate-source voltage. This decay is smaller when the magnitude of the gate-source voltage is smaller. That is the reason why the measured dynamic curve of the mixing product is not horizontal but elevating approaching the zero gate-source voltage.

VII. Conclusion

In the paper a new approach, the parametric method is presented to describe the operation of combined optical-microwave mixing processes. The new approach provides a better description of these processes. The dynamic behavior is investigated in detail. A remarkable decrease in the mixing product is obtained with increasing optical modulation frequency. There are two reasons for it: the time constant exhibited by the depletion region between the substrate and the epitaxial layer and the optically induced substrate current which is increasing with the modulation frequency and doesn't contribute to the mixing effect.

References

[1] H. R. Fetterman and D. C. Ni, "Control of millimeter wave devices by optical mixing," *Microwave Opt. Tech. Lett.*, vol. 1, no. 1, pp. 34–39, Mar. 1988.

[2] D. C. Ni, H. R. Fetterman, and W. Chew, "Millimeter wave generation and characterization of a GaAs FET by optical mixing," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 608–613, May 1990.

[3] Z Urey, D. Wake, D. J. Newson, and I. D. Henning, "Comparison of InGaAs transistors as optoelectronic mixers," *Electron. Lett.*, vol. 29, no. 20, pp. 1796–1797, Sept. 1993.

[4] S. Malone, A. Paolella, P. R. Herczfeld, and T. Berceli, "MMIC compatible lightwave-microwave mixing techniques," in *IEEE MTT Int. Microwave Symp.*, Albuquerque, June 1992, pp. 757–760.

[5] A. Paolella, S. Malone, P. R. Herczfeld, and T. Berceli, "MMIC compatible lightwave-microwave mixing technique," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 518–522. Mar. 1995.

[6] A. Paolella, A. Madjar, and P. R. Herczfeld, "Modeling the GaAs MESFET's response to modulated light at radio and microwave frequencies," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 1122–1130, July 1994.

[7] A. Madjar, P. R. Herczfeld, and A. Paolella, "A novel analytical model for optically generated currents in GaAs MESFET's," *IEEE Trans. Microwave Theory Tech.*, vol. 40, Aug. 1992.

[8] T. Berceli, P. R. Herczfeld, and A. Paolella, "A new high-efficiency optical-microwave mixing procedure," in *23rd Euro. Microwave Conf. Proc.*, Madrid, Spain, Sept. 1993, pp. 317–319.

[9] T. Berceli, "A new optical reception method using microwave subcarriers," in *24th Euro. Microwave Conf. Proc.*, Cannes, France, Sept. 1994, pp. 1679–1684.

[10] ——, "A MMIC based new lightwave-microwave phase detector," in *21st Euro. Microwave Conf. Proc.*, Stuttgart, Germany, Sept. 1991, pp. 1311–1316.

[11] T. Berceli and A. Chapman, "Improved linearity of MESFET amplifiers with optical illumination," in *17th Euro Microwave Conf. Proc.*, Rome, Italy, 1987, pp. 814–819.

[12] C. Rauscher, L. Goldberg, and S. Yurek, "GaAs FET demodulator and down-converter for optical-microwave links," *Electron. Lett.*, vol. 22, no. 13, pp. 705–706, June 19, 1986.

[13] T. Berceli, B. Cabon, A. Hilt, A. Ho Quoc, É. Pic, and S. Tedjini, "Dynamic properties of optically controlled FET amplifiers," in *Topical Meeting Opt.-Microwave Interactions*, Paris, France, Nov. 1994, pp. 83–86.

[14] A. Baranyi, T. Berceli, A. Hilt, and J. Ladvánszky, "High-frequency, quasilinear model for MESFET with electro-optical inputs," in *11th Euro. Conf. Circuit Theory and Design*, Davos, Switzerland, Aug. 1993.

[15] T. Berceli, B. Cabon, A. Hilt, A. Ho Quoc, É. Pic, and S. Tedjini, "Dynamic characterization of optical-microwave transducers," in *IEEE MTT Int. Microwave Symp.*, Orlando, FL, May 1995.

Tibor Berceli (S'77–F'94) photograph and biography not available at the time of publication.