Heterodyne Experiments from Millimeter Wave to Optical Frequencies Using GaAs MESFETs Above f_T*

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Abstract

Response of GaAs FETs in mm-wave and optical heterodyne experiments has been obtained at frequencies above the frequency of unity current gain, f_T. In the mixing of two visible lasers, beat frequencies as high as 300 GHz have been observed. These high IFs were down converted to microwave frequencies by radiatively coupling mm-wave local oscillators into the gate region.

Introduction

Substantial efforts are currently being devoted to extending GaAs MESFET operation into the millimeter frequency regime. To date, experimental 0.25 µm gate length devices have exhibited useful gain up to 40 GHz.[1] In the present work GaAs FETs are investigated by operating them as mixers and detectors at much higher frequencies, significantly above f_T. Although a number of studies involving visible radiation have been made using picosecond pulses,[2] the emphasis here is the response to CW sources.

Our results indicate that GaAs FETs can be used as sensitive and versatile detectors and mixers of millimeter wave and optical radiation. As millimeter mixers results have been obtained up to 350 GHz. Exploiting this millimeter wave responsivity, optical mixing between two lasers has been demonstrated with IF frequencies up to 300 GHz.

Device Description and Experimental Procedures

Devices used in the experiments are 0.5 µm gate length MESFETs with a total gate width of 104 µm. The gate fingers are located in a drain-source spacing of ~4 µm. Gate capacitance and transconductance are typically 0.06 pF and 9.5 mS, respectively. Consequently, f_T is approximately 25 GHz. A photomicrograph of a typical device is shown in Fig. 1a. The FETs are mounted in the common source configuration and biased in the linear region. The optical and millimeter wave signals are coupled radiatively into the gate region of the FET, and the IF frequency is detected at the drain terminal in a 50Ω system. The gate terminal is only used if the IF is down converted further by a second local oscillator in the microwave range. Otherwise, the gate terminal is connected to ground via a 50Ω resistor. The 3-way mixing of two optical signals with either a microwave signal or a millimeter wave signal is illustrated in Fig. 2.

Millimeter Wave Mixing

In the millimeter wave and submillimeter wave frequency range the signal is radiatively coupled into the gate region by the fields of a closely spaced waveguide. The coupling is maximized when the E-field is orthogonal to the gate stripe, as indicated in Fig. 1a. Video detection has been obtained up to 800 GHz by this method. Harmonic mixing was performed by combining spatially the fields of a 350 GHz carcinotron with that of a 70 GHz klystron in the vicinity of the gate region. The detected IF is the difference frequency between the ~350 GHz signal and the 5th harmonic of the 70 GHz local oscillator and was typically in the range of 2 to 4 GHz. In the harmonic mixing experiment the signal to noise ratio for the detected IF response was typically on the order of 45 dB.

Optical Mixing

Since millimeter wave detection and mixing has been demonstrated, it becomes feasible to examine optical mixing at very high IF frequencies. Mixing in the optical region was performed by focusing a He-Ne laser at 6328 Å and a tunable stabilized dye laser pumped by an Ar^+ ion laser onto the vicinity of the gate with a ~3 µm diffraction limited spot. Power levels for the He-Ne laser and dye laser were 1 mW and 50 mW, respectively. As an optical detector the signal level was on the order of 60 mV. A summary of mixing experiments in the optical region showing the relevant spectral ranges involved is illustrated in Fig. 3. The stabilized dye laser was tuned away from the He-Ne laser to produce IF frequencies ranging from 100 MHz to 300 GHz. In order to cover this wide IF range three conversion techniques were used in different frequency regimes. Below 20 GHz the IF response was detected directly using a spectrum analyzer. Between 20 and 40 GHz the IF response was heterodyned down to 500 MHz by feeding a microwave local oscillator into the gate terminal of the FET. The power of the microwave local oscillator used

*This work was sponsored by the U.S. Army Research Office and the U.S. Air Force (with specific support by AFOSR).

was approximately 200 mW. Between 40 and 300 GHz, down conversion of the millimeter wave IF signal was achieved by coupling the millimeter wave LO from a carcinotron into the gate region by means of a closely spaced waveguide, as shown in Fig. 4.

As a special case of optical mixing using only one laser, two modes of a He-Ne laser were also mixed in an FET to produce an IF signal of 641 MHz. Plots of the detected IF signal were obtained by scanning the laser beam over the device in order to define the active region as shown in Fig. 1b. Reduced response has also been observed from the mode mixing of a Nd:YAG laser at 1.06 µm, ie., below the GaAs bandgap energy.

Discussion of Results

The frequency limit in most GaAs FET applications arises from the fact that the signal is fed into the gate terminal, which is loaded by the depletion layer capacitance, C_g. As a result, the time constant associated with C_g and the transconductance, g_m, dominates the frequency response of the device. The frequency of unity current gain is given by $f_T = g_m/2\pi C_g$ and consequently is the primary frequency limit when the signal is fed directly into the gate terminal. However, f_T is not necessarily the upper limit when signals are radiatively coupled into the device.

Coupling optical signals into an FET has been reported previously. Optically induced variations of drain current[3,4,5], gate capacitance[6], pinch-off voltage[3], S-parameters[7], and back-gating[5] have also been studied. Applications of the photo-induced effect for tuning the frequency of GaAs FET oscillators[6,8] and for use as high-speed optical detectors[4,7,9,10] have also been demonstrated. The photoresponse mechanism of GaAs FETs proposed by Sugeta and Matsushima[11] is shown in Fig. 5. Optical illumination generates carriers in the depletion layer, which are then swept out by the electric field, producing a photocurrent i_{ph}. The associated gate photovoltage in turn modulates the depletion layer, varying the drain current via the transconductance of the FET. Since modulation of the drain current is based on the photogenerated voltage at the gate terminal, the frequency response of a FET to an intensity modulated optical excitation will still be constrained by f_T -- essentially the same limit as for an FET in a microwave application where the input signal is connected directly to the gate terminal. The above mechanism can be extended to explain optical mixing at IF frequencies below f_T, such as mixing of two modes of a He-Ne laser in an FET to produce carriers at the beat frequency of 641 MHz.

For IF signals significantly above f_T it is not possible for the depletion layer to follow the beat frequency because of long time constants associated with the large depletion layer capacitance. Hence a different mechanism must be responsible for the observed mixing, such as photoconductivity with consequent modulation of the depletion layer and photo-induced effects at the depletion layer edges of the gate. If mixing is produced by a net change in photo-induced carrier density in the FET channel, then the rapid removal of one carrier type from the active device area is required. Both the lifetime and transit time of electrons through the gate region are too long to account for the observed high frequency response. Two possible mechanisms for more rapid carrier removal are the trapping of holes by defect centers or the differences of sweep-out rate of electrons and holes by the electric field. Trapping of holes has been proposed previously to explain the increase of gate capacitance under optical illumination.[6] Then modulation of the drain current results from variation of the channel thickness at the depletion layer edge. In Fig. 6 the response of the depletion layer under the gate to an applied E-field is shown. Because of the built-in potential of the Schottky barrier, charges do not come from the gate metal, but rather they originate near the boundary of the depletion layer. If the charges induced by the radiatively coupled E-field are confined to the edges of the gate, then modulation of the current in the channel takes place. The high frequency response follows by virtue of the small incremental capacitance associated with the depletion layer edge rather than with the large capacitance of the entire depletion layer. In the case of millimeter wave mixing a second E-field is radiatively coupled in, to down-convert to IF frequenies which are detected at the drain terminal. Mixing could arise from nonlinearities in the junction or from channel modulation effects.

Summary and Conclusions

A number of experiments are in progress to determine the relative importance of the mechanisms giving rise to mixing in an FET over a broad frequency range. More complex mechanisms than those discussed above may have to be invoked to explain the response that has been observed in the saturated current regime, and the reduced response observed from the mode mixing of a Nd:YAG laser at 1.06 µm, below the band gap energy.

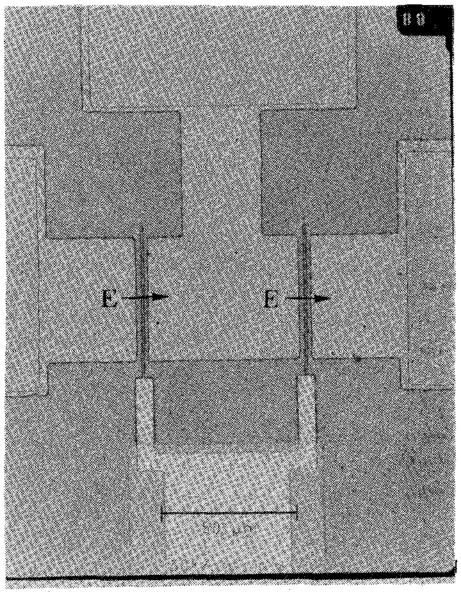
In view of the inefficient coupling of millimeter wave and optical signals into the device, it seems appropriate to consider device configurations that might provide tighter coupling. Gamel and Ballantine[3] have proposed coupling the optical signal into the FET using an optical waveguide positioned parallel to the FET gate. The analogous device for mixing in the millimeter wave region would utilize a dielectric waveguide parallel to the gate. Devices without gates could also be fabricated to test the relative importance of the depletion layer in optical and millimeter wave mixing. A second possibility is using GaAs optical or millimeter waveguide on a layer of SiO_2 and thereby fabricating the device as an integral part of the guide. GaAs and InP optical waveguides fabricated using epitaxial overgrowth have been reported by Leonberger and coworkers.[12] We suggest the fabrication of FETs on an n-type layer grown over the semi-insulating waveguiding structure. In this second approach the waves would be propagating within the device rather than coupling to the fringing fields. Experimental devices such as those described may provide better coupling to the optical or millimeter waves, as well as a means to obtain additional data for the understanding of the physical mechanisms which produce mixing in FETs at high frequencies.

Acknowledgment

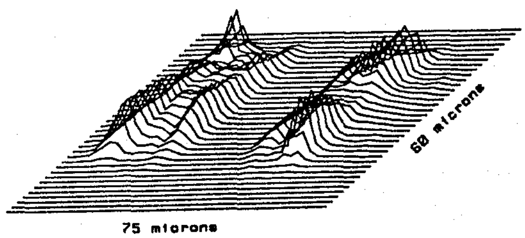
A. Gopinath contributed to the design and fabrication techniques of the 0.5 µm gate FETs. M. W. Pierce, G. A. Lincoln and G. R. Durant provided valuable technical assistance in the fabrication of the FETs. W. Macropoulos and A. R. Forte contributed their expertise in packaging the devices. The authors are indebted to W. E. Courtney, A. J. Seeds and R. A. Murphy for many technical discussions.

References

1. E. T. Watkins, H. Yamasaki, and J. M. Shellenberg, ISSCC Digest of Technical Papers, pp. 198-199, Feb. 1982.
2. P. R. Smith, D. H. Auston, and W. M. Augustyniak, Appl. Physics Lett., vol. 39, pp. 739-741, Nov. 1981.
3. J. Graffeuil, P. Rossel, and H. Mortinot, Electronic Lett., vol. 13, pp. 439-440, July 1979.
4. J. C. Gammel and J. M. Ballantyne, IEDM Digest of Technical papers, pp. 120-123, Dec. 1978.
5. W. D. Edwards, Elect. Dev. Lett., vol. EDL-1, pp. 149-150, Aug. 1980.
6. J. J. Sun, R. J. Gutman, and J. M. Borrego, Solid-State Electronics, vol. 24, pp. 935-940, Oct. 1981.
7. J. J. Pan, SPIE, vol. 150, Laser and Fiber Optics Communications, pp. 175-184, 1978.
8. A. A. Salles and J. R. Forrest, Appl. Physics Lett., vol. 38, pp. 392-394, March 1981.
9. J. M. Osterwalder, and B. J. Rickett, Proc. IEEE, vol. 69, pp. 966-968, June 1979.
10. C. Baak, G. Elze, and G. Walf, Electron. Lett.,vol. 13, p. 193, March 1977.
11. T. Sugeta and Y. Matsushima, Japanese J. of Appl. Phys., vol. 19, pp. L27-L29, Jan. 1980.
12. F. J. Leonberger, C. O. Bozler, R. W. McClelland, and I. Melngailis, J. Appl. Phys. Lett., vol. 38, pp. 313-315, Mar. 1981.



(a)



(b)

Figure 1. (a) Photomicrograph of 0.5 µm x 104 µm gate GaAs FET. b) Scanning plots of beat frequency from mixing two modes of a He-Ne laser in 0.5 µm gate device.