A Heterodyne Receiver for 40-GHz-Modulated 1.3-μm Optical Signals Using a Multi-Tasked InP-Based HEMT

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Abstract — Heterodyne reception of a millimeter-wave modulated 1.3-μm optical carrier signal is achieved with an InP-based HEMT that performs four simultaneous functions all in one. The functions comprise carrier demodulation, generation of a local oscillation signal, frequency multiplication thereof, and transistor-internal down-conversion of the modulation signal to a lower intermediate frequency band. The measured performance characteristics of the heterodyne receiver are reported together with results derived from a systematic study of optical detection and mixing properties of a HEMT by itself, observed as functions of modulation signal frequencies up through 40 GHz and bias conditions.

I. Introduction

Motivated by steady advances in millimeter-wave semiconductor device and circuit technology, research on optical fiber-based techniques has made significant strides toward accommodating ever-higher carrier modulation frequencies. Among the envisioned systems applications for such techniques are the realization of signal delay and signal distribution functions at millimeter wavelengths. In exploratory demonstrations, high-frequency p-i-n photodetectors [1] have commonly been employed to retrieve millimeter-wave modulation signals from optical carriers, with conventional high-frequency amplifier, oscillator and mixer circuitry relied on to transpose recovered modulation signals to lower intermediate frequencies for further processing. The utilization of 1.3-μm-wavelength optical carriers is of particular interest in this context, as it offers minimum signal dispersion and near-minimum signal attenuation in stepped-index single-mode fibers. The objective of the current study has been to explore a HEMT alternative to more conventional 1.3-μm-wavelength receiver approaches.

Supported by earlier work on self-oscillating GaAs FET frequency multipliers [2] and GaAs FET optical receivers at shorter wavelengths [3,4], the concept involves the use of a single InP-based HEMT, surrounded by passive circuitry, to yield a compact, self-contained optical receiver in which the transistor is tasked with performing four simultaneous functions all in one. The tasks encompass photodetection of millimeter-wave signal information superimposed on an optical carrier, self-generation of a local oscillation signal, frequency multiplication of the local oscillation signal with the help of transistor-internal nonlinearities, and the further utilization of these nonlinearities to achieve an intermediate frequency response through mixing of the detected modulation signal with either the local oscillation signal itself or with a generated harmonic thereof. The approach has, indeed, proved practicable, as the results obtained from the experimental 40-GHz receiver circuit presented in Section IV will demonstrate.

II. The HEMT as Optical Detector

Fundamental to the approach is the ability of the employed transistor to act as an efficient optical detector. As is commonly recognized [5,6], both MESFET and HEMT devices, in principle, can be used for this purpose. In the present context, the choice of transistor remains confined to devices whose active channels are composed of semiconductor materials with bandgaps narrower than .95 eV to permit electron-hole pair generation by incident 1.3-μm-wavelength light. Likewise, it is important that all semiconductor layers through which the light must initially pass before reaching the channel be configured to allow maximum utilization of incident optical signal power.

The transistor employed in the investigation is a General Electric InP-based HEMT [7]. The measured photodetection properties of this device as a function of optical carrier modulation frequency is depicted in Fig. 1. For this measurement, the HEMT was mounted in a doubly terminated 50-ohm test fixture and provided with a gate-source bias voltage V_{GS} of 0V and a drain-source bias voltage V_{DS} of +1.0V. The gross optical signal power incident on the transistor was 6 dBm, obtained with two heterodyned Nd:YAG lasers [8] and focused into a 20-μm-diameter spot at a 75-degrees angle to the device surface to prevent shadowing by the mushroomed gate structure. Of the available power, due to the limited optical spot diameter, an estimated ten percent was actually absorbed in the device through the 1.5-μm-wide gap between gate and drain metallizations.

The curve shown in Fig. 1 displays typical photoconductive behavior with a sharp drop in output signal intensity as holes cease to participate in the process with increasing frequency. The general frequency behavior is quite independent of bias conditions, as is apparent in Figs. 2 and 3, where HEMT detector characteristics have been plotted against gate-source

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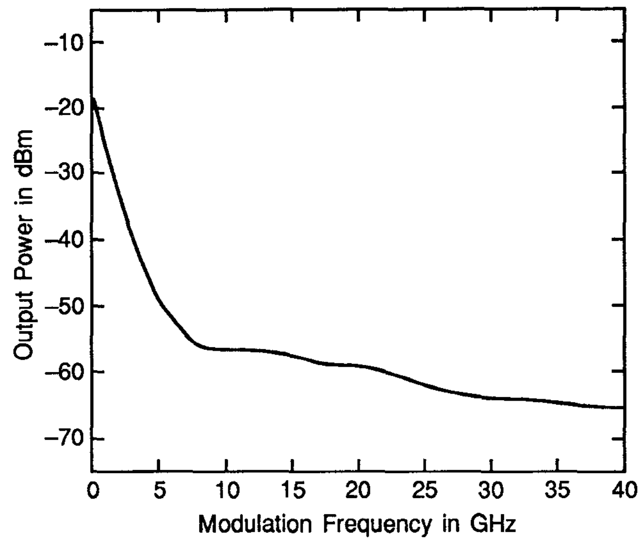

Fig. 1. HEMT photodetection as function of optical carrier modulation frequency for an incident optical signal level of 6 dBm, and for gate-source and drain-source bias voltages of V_{GS} = 0V and V_{DS} = 1.0V, respectively.

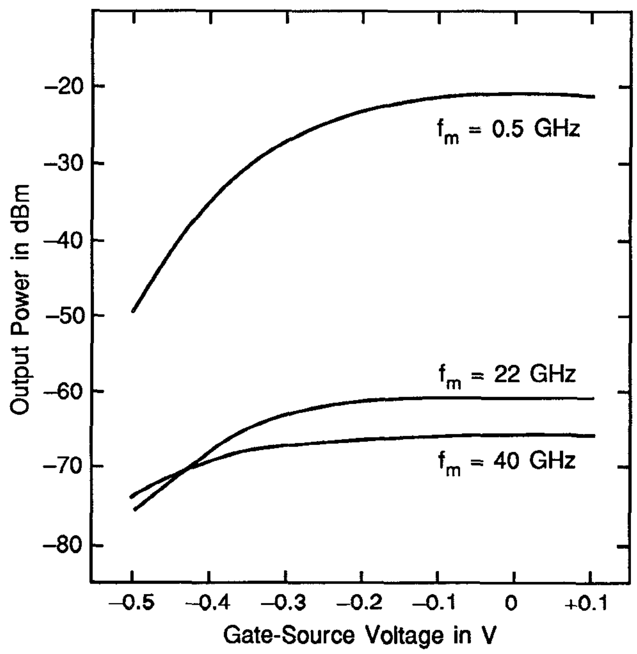

Fig. 2. HEMT photodetection as function of gate-source bias voltage for V_{DS} = 1.0V at an incident optical signal level of 6 dBm.

and drain-source bias voltages, respectively, for three different values of optical carrier modulation frequency. Aside from the frequency dependence and in accordance with expectations,

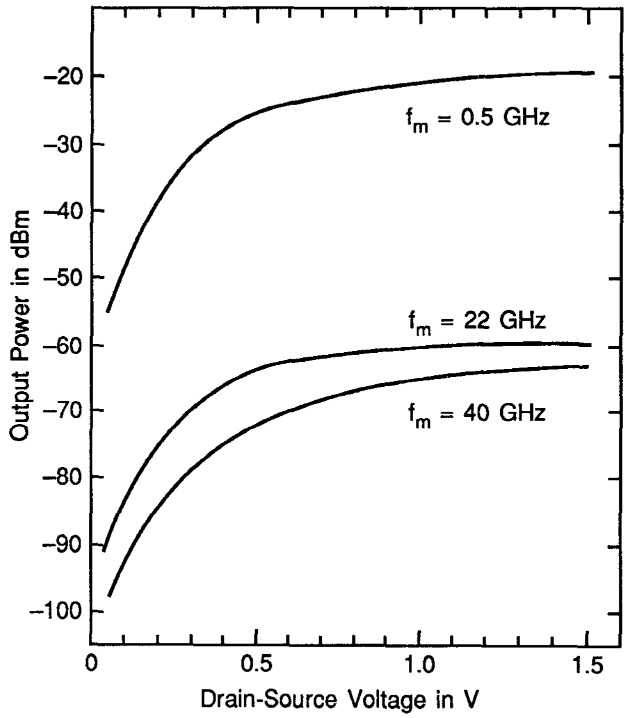

Fig. 3. HEMT photodetection as function of drain-source bias voltage for V_{GS} = 0V at an incident optical signal level of 6 dBm.

detector output signal strength rolls off as gate-source bias voltages drop below the pinch-off voltage of around - 0.4V and as drain bias currents drop below the saturation points in the HEMT static current-voltage characteristics.

III. The HEMT as Downconverter

To investigate the ability of the HEMT to serve as downconverter, a 22-GHz external local oscillation signal was injected into the gate port of the test device, with its output port again terminated in 50 ohms. The injected signal was confined to a low -30-dBm level to assure true small-signal operation without concern for obscuring large-signal effects. Both the upper and lower sideband responses of the HEMT were measured as functions of gate-source and drain-source bias voltages for an intermediate frequency of 2 GHz, with Figs. 4 and 5 exhibiting samples of the acquired data. It should be stressed that the observed low levels of output signal are determined, in part, by the mentioned low level of applied local oscillation signal and are hence not representative of what can be typically obtained.

Although in most instances - including ones that involved other frequency combinations - lower and upper sideband responses were found to be virtually identical, as anticipated, some responses exhibited pronounced dips, such as the one contained in Fig. 4. The presence of such dips were found to be highly sensitive to lateral positioning of the illumination spot

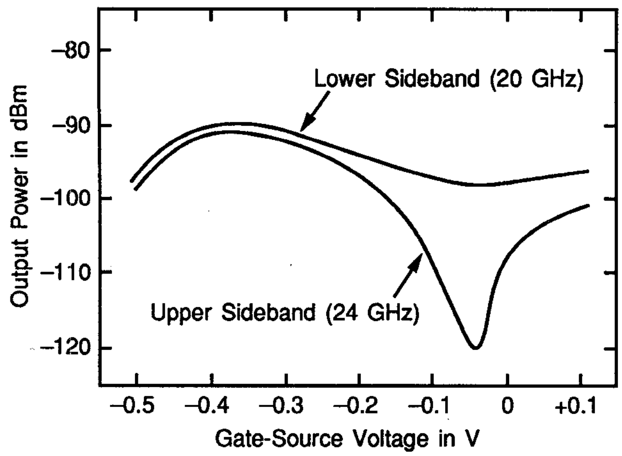

Fig. 4. HEMT downconversion characteristics for an incident optical signal level of 6 dBm and a gate-port-injected 22-GHz local oscillation signal level of -30 dBm as function of gate-source bias voltage for V_{DS} = 1.0V.

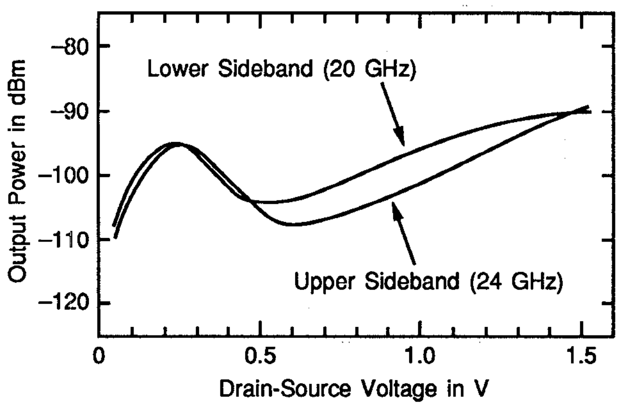

Fig. 5. HEMT downconversion characteristics for an incident optical signal level of 6 dBm and a gate-port-injected 22-GHz local oscillation signal level of -30 dBm as function of drain-source bias voltage for V_{GS} = 0V.

along the gate-drain gap. This supports the hypothesis that both transconductance and output conductance nonlinearities engage in the downconversion process, with the observed dips the result of destructive signal interference.

IV. A 40-GHz HEMT Optical Receiver

Through the choice of suitable semiconductor materials and the presence of intrinsic device nonlinearities, a transistor is inherently capable of performing optical detection and mixer functions simultaneously, as illustrated by the results just described. The full potential of a transistor is not fully realized, however, unless its active-circuit properties are exploited, also. Within the context of 1.3-μm-wavelength reception, this is achieved through HEMT self-generation of the required local oscillation signal. In addition, device nonlinearities may be used to frequency multiply the self-generated local oscillation signal and thereby provide the option of subharmonically pumped downconversion. This relaxes transistor requirements at the fundamental oscillation frequency and brings millimeter-wave signal reception into convenient reach.

The general circuit design concept of employing a multi-tasked transistor to receive millimeter-wave modulated optical signals of 1.3 μm carrier wavelength derives from the work with multi-tasked GaAs FETs at shorter optical wavelengths [3,4] referred to earlier. In the new HEMT-based design, special care has been taken, however, to maximize 40-GHz receiver efficiency through control of circuit-internal impedance matching conditions at key signal component frequencies. The imposed conditions include the presentation of high circuit impedance values to the drain-source port of the HEMT at the 40-GHz nominal incident modulation signal frequency and at the 44-GHz harmonic of the selected 22-GHz local oscillation frequency. This is done to enhance the utilization of transistor output conductance nonlinearities in the downconversion and frequency multiplication processes. The conditions also include suppression of transistor-external drain-to-gate feedback at these same frequencies in accordance with earlier findings [2].

A close-up view of the composite 40-GHz receiver circuit is shown in Fig. 6. The left-hand portion of the circuit contains the multi-tasked InP-based HEMT with its surrounding circuitry. The right-hand portion of the circuit encompasses a broadband buffer amplifier that utilizes an Avantek M106L GaAs FET and provides 7 dB of gain at the nominal intermediate frequency of 4 GHz. The measured performance of the receiver for a fixed incident optical signal level of 6.5 dBm is contained in Fig. 7. The four individual curve segments correspond to the

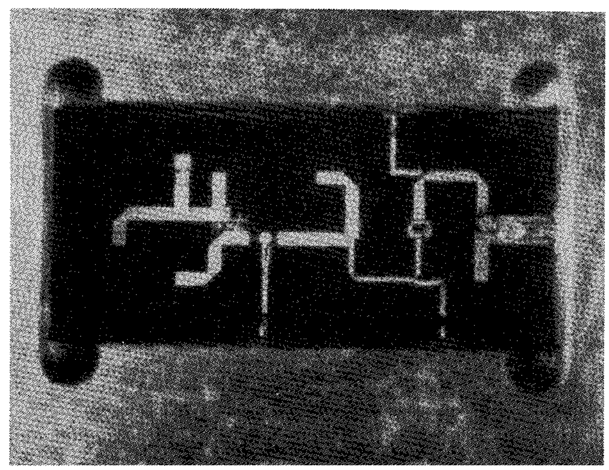

Fig. 6. Single-HEMT 40-GHz receiver for 1.3-μm-wavelength optical signals.

receiver direct-detection, 22-GHz-lower-sideband, 22-GHz-upper-sideband, and 44-GHz-lower-sideband responses, respectively, as modified by the buffer amplifier frequency response. Aside from the direct-detection response which benefits from hole participation, the largest of the response peaks occurs, in accordance with original design objectives, at 40 GHz, generated through subharmonically pumped downconversion.

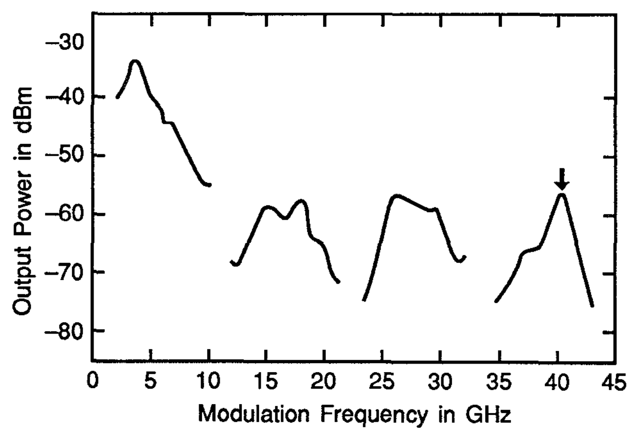

Fig. 7. Frequency response of the 40-GHz optical receiver for a constant incident signal level of 6.5 dBm.

A comparison of the 40-GHz peak response of -56 dBm with the photodetection response of -65 dBm at 40 GHz for the HEMT by itself (Fig. 1), after accounting for 7 dB of buffer amplifier gain, yields an effective downconversion gain of 2 dB. This is a respectable result, considering that it is achieved through mixing of the detected signal with a self-generated harmonic of a self-generated local oscillation signal. As for the photodetection process itself, based on an estimated four-to-five percent quantum efficiency [1] of the thin active layer (commensurate with the originally intended 100-GHz use of the transistor) and the already mentioned 10-percent fractional interception of the incident light beam, achieved photoconductivity properties conform very closely to expectations.

V. Conclusions

The experimental results presented above demonstrate how a single InP-based HEMT can serve as the nucleus of a receiver for millimeter-wave modulated 1.3-µm-wavelength optical signals. The HEMT is thereby tasked with the four simultaneous transistor-internal functions of optical carrier demodulation, self-oscillation, frequency multiplication, and downconversion. Observed conversion efficiencies show good agreement with estimates derived from transistor geometric and material considerations. Constraints were imposed, however, on the proof-of-concept experiment through the use of a transistor whose high-frequency capabilities far exceeded minimum requirements and through the absence of more sophisticated optical means to project the incident light beam onto the narrow gate-drain gap in the transistor metallization pattern. In an actual systems application, a boost in conversion efficiency would naturally be sought and achieved through reliance on a transistor with a wider gate-drain metallization gap and a considerably thicker channel region in order to maximize interception and absorption of available incident light.

Acknowledgements

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