INP GUNN DEVICES AND GAAS TUNNETT DIODES AS LOW-NOISE HIGH-PERFORMANCE LOCAL OSCILLATORS IN FUNDAMENTAL MODE

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Abstract

Improved fabrication technologies significantly increased the RF power levels that are available from GaAs TUNNETT diodes and InP Gunn devices. RF power up to 100 mW around 105 GHz and more than 100 mW around 132 GHz were obtained from TUNNETT diodes and Gunn devices, respectively. Corresponding dc-to-RF conversion efficiencies reach 6 % in TUNNETT diodes and 2.5 % in Gunn devices. Free-running oscillators with both types of devices exhibit excellent noise performance up to the highest power levels and typical phase noise, measured at a frequency off-carrier of 500 kHz, is below - 94 dBc/Hz for TUNNETT diodes and below - 100 dBc/Hz for Gunn devices. At lower power levels, TUNNETT diodes show the best noise measure (< 20 dB) of any two-terminal devices.

1. Introduction

Low-noise fundamental sources in the 100-170 GHz range with significantly increased RF output power are required to drive high-power high-efficiency multiplier stages and are one key element in reaching RF power levels of more than 0.1 mW at 1 THz. The RF power output of most two-terminal devices at millimeter-wave frequencies is limited by the tolerable active-layer temperature, and diamond with its high thermal conductivity is a preferred heat sink material. As shown in Figure 1, a simple analysis [1] indicates that the thermal resistance of GaAs-based (and similarly InP-based) devices is reduced by at least a factor of two on diamond heat sinks [2]. Therefore, devices on diamond heat sinks can handle more than twice the dc input power at the same operating active-layer temperature, and this is expected to more than double the available RF output power. To demonstrate this potential, a selective etching technology originally developed for GaAs IMPATT diodes was adopted and modified for various GaAs and InP-based two-terminal devices. The design of the devices and additional theoretical investigations were published previously [3-5] and are not repeated here. Not only the power capabilities but also excellent noise properties at the maximum available power are required for their use in low-noise receivers. Therefore, the spectra of free-running oscillators were monitored from intermediate up to the highest power levels, and the FM noise measure was extracted from these measurements.

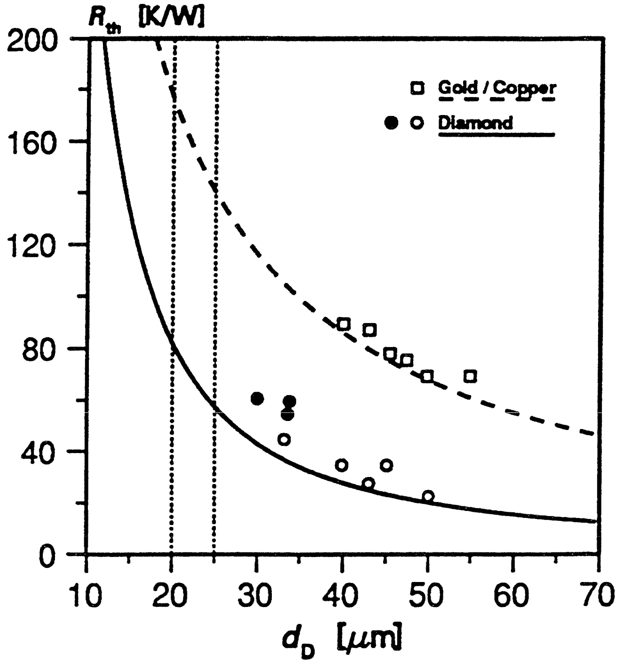

Figure 1: Predicted thermal resistances of diodes on diamond heat sinks (——) and integral heat sinks (- - -) as a function of the diode diameter. Measured thermal resistances of GaAs W-band (●), V-band (○) IMPATT diodes on diamond heat sinks, and GaAs V-band IMPATT diodes on integral heat sinks (❑).

2. Device Technology

The selective etching technology for devices to be mounted on diamond heat sinks was originally developed for GaAs W-band IMPATT diodes [6] and was subsequently modified for different device structures [2,7] in both GaAs and InP material systems. The basic steps are as follows:

- The epitaxial side of the entire sample is coated with the metal layers for the ohmic contact (Ti/Pt/Au for p type and AuGeNi/Ti/Au for n type).
- A supporting grating is selectively electroplated onto the metallization for mechanical support during the final processing steps.
- The sample is glued on a carrier epitaxial side down, and the subtrate is removed in the first selective etch.

- The etch-stop layer is removed in the second selective etch (obligatory for AlGaAs/GaAs, optional for InGaAs/InP).
- The metal layers for the n ohmic contact (AuGeNi/Ti/Au) are deposited and selectively electroplated with a few microns of gold.
- The device mesa is etched and the sample is removed from the carrier.
- The ohmic contacts are annealed on a hotplate in a nitrogen atmosphere.
- The sample is diced into individual devices, and single devices are thermocompression bonded onto metallized diamond heat sinks.

In order to obtain from one wafer InP Gunn devices with either orientation of the grading [8], the order of the first five steps had to be reversed.

3. RF Performance

The GaAs TUNNETT diodes were evaluated in the WR-10 waveguide version of a standard full-height waveguide resonant-cap cavity [9] and the InP Gunn devices, in the WR-6 waveguide version [2]. Only a back short at one flange of the cavity was used to tune for maximum RF output power, and no other tuning elements such as an E-H tuner were found necessary for TUNNETT diodes and Gunn devices. Figure 2 summarizes the results of ten GaAs TUNNETT diodes on diamond heat sinks with power levels up to 100 mW between 100 GHz and 105 GHz and dc-to-RF conversion efficiencies above 5 % around 105 GHz. Figure 3 summarizes the results of the best InP Gunn in fundamental mode with RF power levels of more than 100 mW and dc-to-RF conversion efficiencies up to 2.5 % around 132 GHz. Most devices were evaluated at up to seven different frequencies and RF power levels of more than 40 mW around 150 GHz and more than 15 mW at 159 GHz were obtained from the best devices on diamond heat sinks. To the authors' knowledge, these are the highest values reported to date and they exceed those of InP Gunn devices in second-harmonic mode around 140 GHz [10]. Figure 4 shows the performance of one InP Gunn device as a function of the dc bias. The position of the back short was tuned for maximum RF output power (> 100 mW) at maximum bias and kept fixed throughout the measurement. For input power levels between about 3 W and 4.2 W, the device operates in a stable single mode, and the oscillation frequency drops monotonically by more than 250 MHz. This allows simple electronic tuning through the bias in a phase-locked loop. The insert of Figure 3 also shows the nominal doping profile of the n^+nn^+ epitaxial layers. At maximum applied bias, the frequency tuning range of the backshort was measured for the same Gunn device. As can be seen from Figure 5, fundamental-mode operation allows smooth tuning with the backshort as the only tuning element. No mode jumps occur and the drop in RF output power remains below 2 dB between 131 GHz and 135.5 GHz. Over a smaller tuning range of about 3 GHz, the RF power decreases by less than 1 dB.

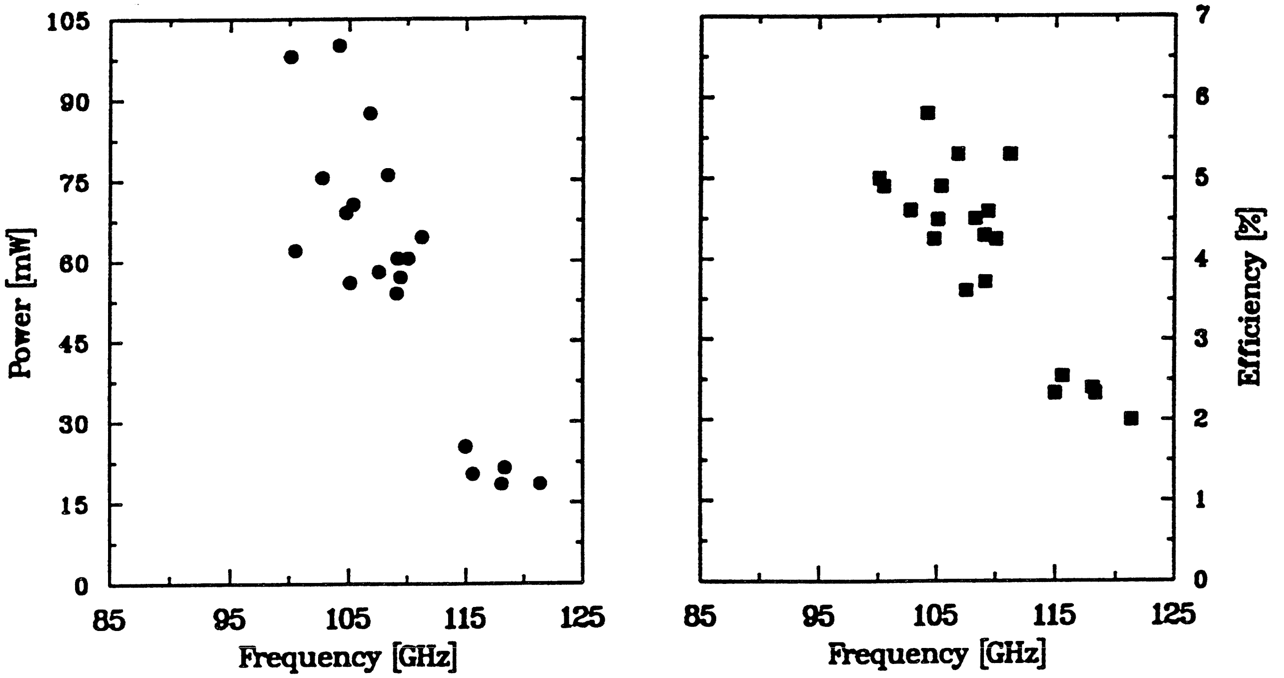

Figure 2: Output power (●) and efficiency (■) versus oscillation frequency in W-band for different GaAs TUNNETT diodes on diamond heat sinks.

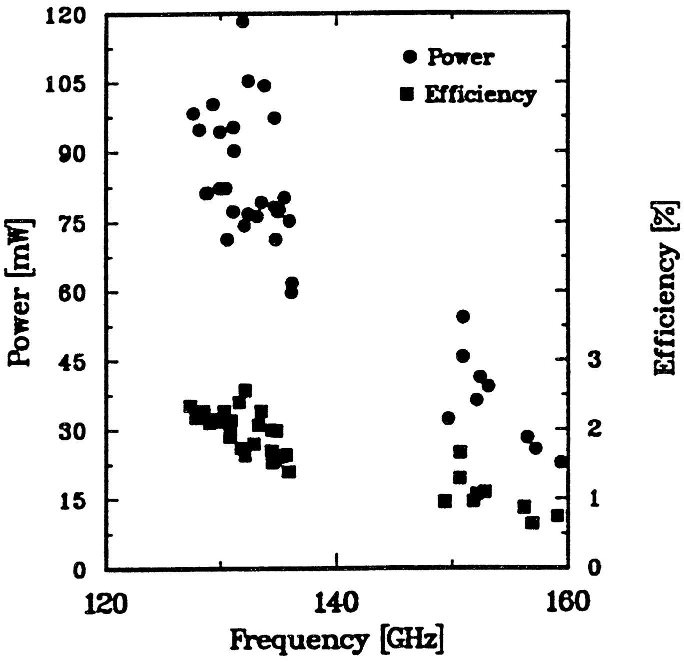

Figure 3: Output power (●) and efficiency (■) versus oscillation frequency in D-band for different InP Gunn devices on diamond heat sinks.

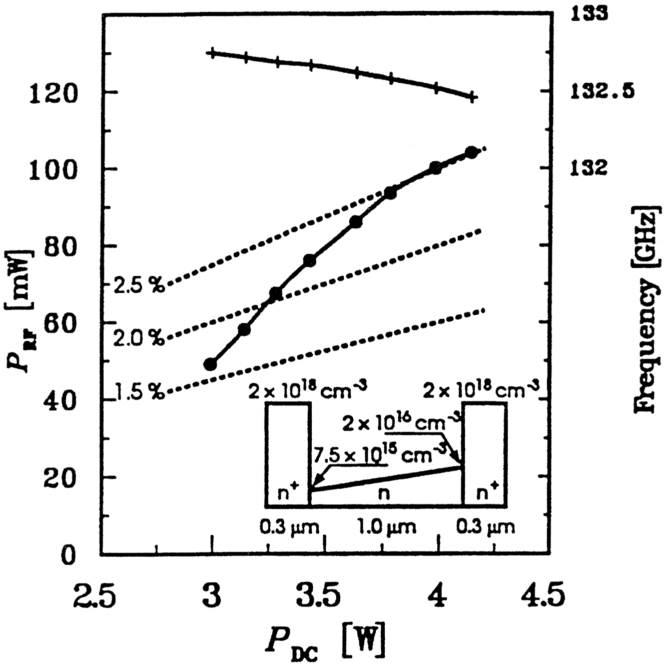

Figure 4: Bias-dependent RF characteristics of a D-band InP Gunn device (●: output power, +: oscillation frequency, - - -: lines of constant efficiency).

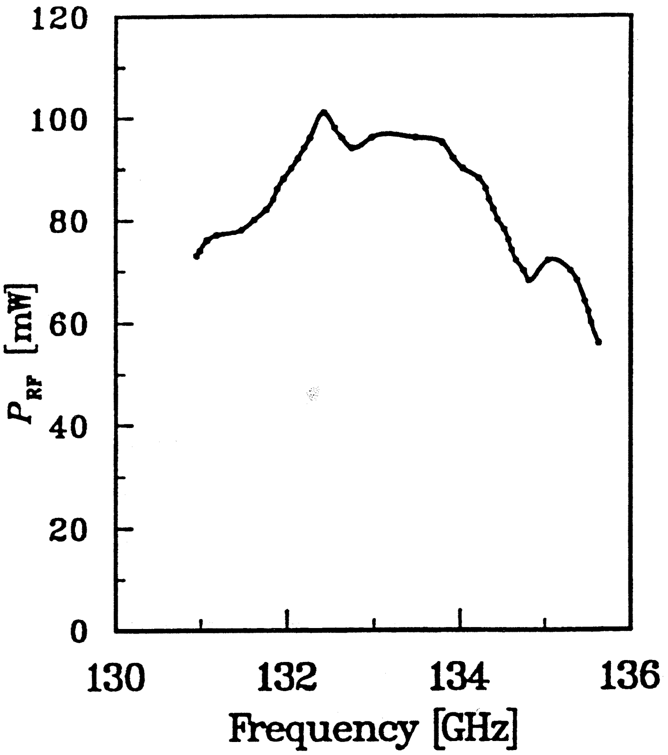

Figure 5: Tuning characteristics of a D-band InP Gunn device at maximum dc bias.

4. Noise Performance

Free-running oscillators with either TUNNETT diodes or Gunn devices exhibit clean spectra up to the highest RF output power. Typical phase noise is below - 94 dBc/Hz for TUNNETT diodes and - 100 dBc/Hz for Gunn devices both at a frequency off-carrier of 500 kHz. Figures 6 and 7 show examples for a TUNNETT diode with an RF output power of 40 mW at an oscillation frequency of 109.047 GHz and for a Gunn device with 41 mW at 134.791 GHz. The noise measure M

$$M = \frac{\Delta f_{\mathrm{rms}}{}^2 Q_{\mathrm{ex}}{}^2}{f_{\mathrm{o}}{}^2 k T_0 B} P_{\mathrm{RF}}$$

allows a better comparison between different types of devices. The effective frequency deviation Δf_{rms} at the frequency off-carrier f_{m} is derived from the phase-noise-to-carrier ratio N/C above

$$\Delta f_{\mathrm{rms}}{}^2 = 2(N/C) f_{\mathrm{m}}{}^2 \ ,$$

and the loaded Q value (Q_{ex}) is determined using a self-injection locking technique with a directional coupler (measured coupling value 21 dB) and a tunable short [11]. The noise measure of TUNNETT diodes at high RF power levels ranges from 22 dB to 27 dB, and examples are 22 dB at 60 mW and 111.15 GHz, 24 dB at 76 mW and 108.33 GHz, and 26 dB at 55 mW and 109.56 GHz. Loaded Q values range from 32 to 64. Lower values for M were obtained at intermediate power levels, *e.g.*, 20 dB at 5.2 mW and 102.46 GHz and below 18 dB at 11 mW and 104.05 GHz. To the authors' knowledge these are the best values for any oscillator with two-terminal devices in this frequency range and they confirm that tunneling is the dominant mechanism in the carrier injection of these TUNNETT diodes. Examples for the noise measure of Gunn devices at high RF power levels are 25 dB at 44 mW and 132.38 GHz and 23 dB at 35 mW and 134.82 GHz [7] with loaded Q values ranging from 60 to 120. Noise data are quite sparse at D-band frequencies, are limited to transit-time diodes and mainly cover the typically better small-signal case [12-14]. These D-band InP Gunn devices show better noise performance than present transit-time diodes with high multiplication factors (IMPATT and MITATT diodes in GaAs and Si) [12-14] and, probably due to easier impedance matching, offer higher RF power levels and dc-to-RF conversion efficiencies than present GaAs single-drift IMPATT and MITATT diodes [13-15] at these D-band frequencies. They even approach the RF performance of Si double-drift IMPATT diodes [16-17].

The $^1/_f$ corner frequency in Δf_{rms} is on the order of 100 kHz (< 500 kHz) for the investigated TUNNETT diodes and Gunn devices, and the phase noise typically reaches the noise floor of the spectrum analyzer with the harmonic mixer around 1 MHz for TUNNETT diodes and Gunn devices. Therefore, it is not clear at this point whether the higher values in the noise measure of TUNNETT diodes are caused by $^{1}/_{f}$ (flicker) noise components. The phase noise of the best Gunn device in Figure 4 reaches the noise floor below a frequency off-carrier of 500 kHz and, therefore, its noise measure is assumed to be well below 25 dB for the highest power levels around 132 GHz.

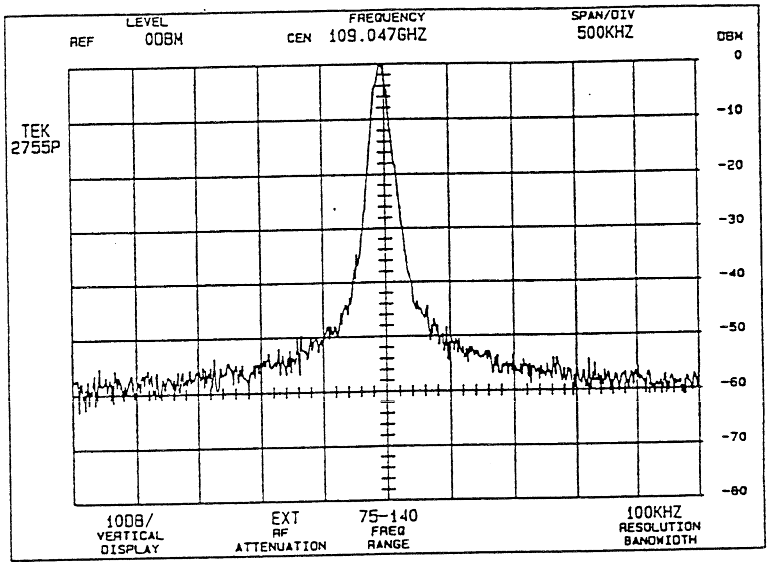

Figure 6: Spectrum of a GaAs W-band TUNNETT diode free-running oscillator, power level 40 mW, center frequency 109.047 GHz, vertical scale 10 dB/div, horizontal scale 500 kHz/div, BW 100 kHz.

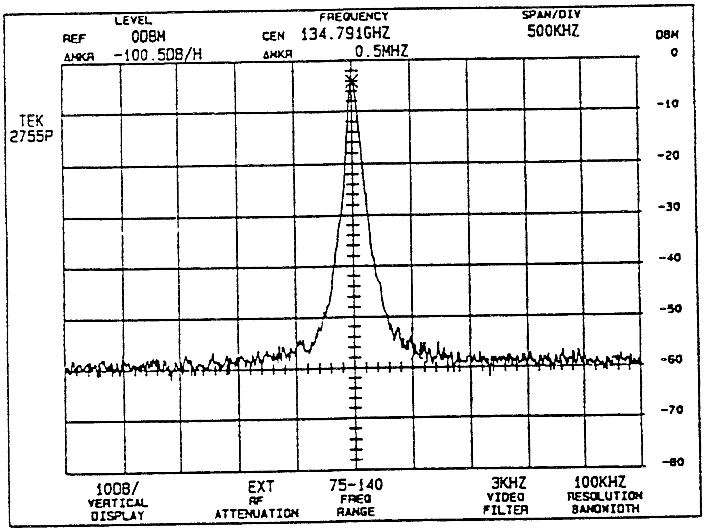

Figure 7: Spectrum of an InP D-band Gunn device free-running oscillator, power level 41 mW, center frequency 134.791 GHz, vertical scale 10 dB/div, horizontal scale 500 kHz/div, BW.100 kHz, VBW 3 kHz.

5. Conclusion

GaAs TUNNETT diodes and InP Gunn devices in fundamental mode reach the highest power levels of any GaAs- and InP-based two-terminal devices. Their excellent noise performance makes them ideally suited for local oscillators and drivers for multiplier chains. Still higher power levels and oscillation frequencies can be expected from more optimized devices.

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