Ninth International Symposium on Space Terahertz Technology, March 17-19, 1998, Pasadena, California.

GAAS TUNNETT DIODES AND INP GUNN DEVICES FOR EFFICIENT SECOND-HARMONIC POWER GENERATION ABOVE 200 GHZ

Heribert Eisele

Solid-State Electronics Laboratory
Department of Electrical Engineering & Computer Science
1246B EECS Building
The University of Michigan
Ann Arbor, Michigan 48109-2122

Abstract

Low-noise operation and significant RF power levels were demonstrated recently with GaAs TUNNETT diodes and InP Gunn devices in fundamental-mode operation at W-band (75-110 GHz) and D-band (110-170 GHz) frequencies. State-of-the-art RF power levels of 100 ± 5 mW at 100-107 GHz from TUNNETT diodes as well as > 200 mW at 103 GHz, > 130 mW around 132 GHz, and > 80 mW at 152 GHz from Gunn devices were measured, which correspond to dc-to-RF conversion efficiencies of 5.8-6.1 % at 100-107 GHz, > 2.3 % at 103-132 GHz, and > 1.4 % at 152 GHz. As shown with the first experimental results, *e.g.*, RF power levels of > 0.3 mW at 283 GHz from Gunn devices and > 0.6 mW at 210 GHz from TUNNETT diodes, both two-terminal devices exhibit strongly nonlinear characteristics. Therefore, second-harmonic power generation was investigated further theoretically and experimentally. State-of-the-art RF power levels of 9 mW at 209 GHz and > 4 mW at 235 GHz from TUNNETT diodes as well as more than 1 mW at 280 GHz from Gunn devices were measured with a submillimeter-wave dry calorimeter. Corresponding dc-to-RF conversion efficiencies were > 1 % at 209 GHz and > 0.6 % at 235 GHz. Simulations revealed a large modulation in the depletion width of the TUNNETT diodes and explained the high up-conversion efficiencies observed. The results from TUNNETT diodes compare favorably with those from Schottky varactor diode frequency multipliers that are driven by transferred-electron oscillators. As expected from the excellent noise performance in the fundamental mode, these free-running oscillators showed clean spectra with a low phase noise of, *e.g.*, well below - 94 dBc/Hz at a frequency off the carrier of 500 kHz.

1. Introduction

Low-noise operation of free-running oscillators and significant RF power levels were demonstrated recently with GaAs TUNNETT diodes and InP Gunn devices in fundamental-mode operation at W-band (75-110 GHz) [1] and D-band (110-170 GHz) [2] frequencies. Improved heat dissipation of devices on diamond heat sinks resulted in state-of-the-art RF power levels of 100 ± 5 mW at 100-107 GHz from TUNNETT diodes [1,3] as well as more than 200 mW at 103 GHz, more than 130 mW around 132 GHz, and more than 80 mW around 152 GHz from Gunn devices [2,3]. These RF power levels correspond to dc-to-RF conversion efficiencies of 5.8-6.1 % at 100-107 GHz [1,3], more than 2.3 % at 103-132 GHz, and more than 1.4 % at 152 GHz [2,3]. Figure 1 summarizes these experimental results from TUNNETT diodes and Gunn devices. Tunneling as the injection mechanism in TUNNETT diodes or the formation of domains in Gunn devices causes inherently nonlinear device properties with respect to the RF voltage across the device terminals. In addition, a modulation in the width of the active region corresponds to a capacitance variation and generation of higher harmonics similar to that of Schottky varactor diodes. Second-harmonic power extraction was initially investigated, mainly to confirm fundamental-mode operation, and first experimental results, *e.g.*, RF power levels of more than 0.3 mW at 283 GHz [4] and more than 0.6 mW at 210 GHz [1], indicate that both Gunn devices and TUNNETT diodes hold strongly nonlinear characteristics. As a consequence, second-harmonic power extraction was investigated further experimentally using different waveguide configurations and theoretically using diode simulations.

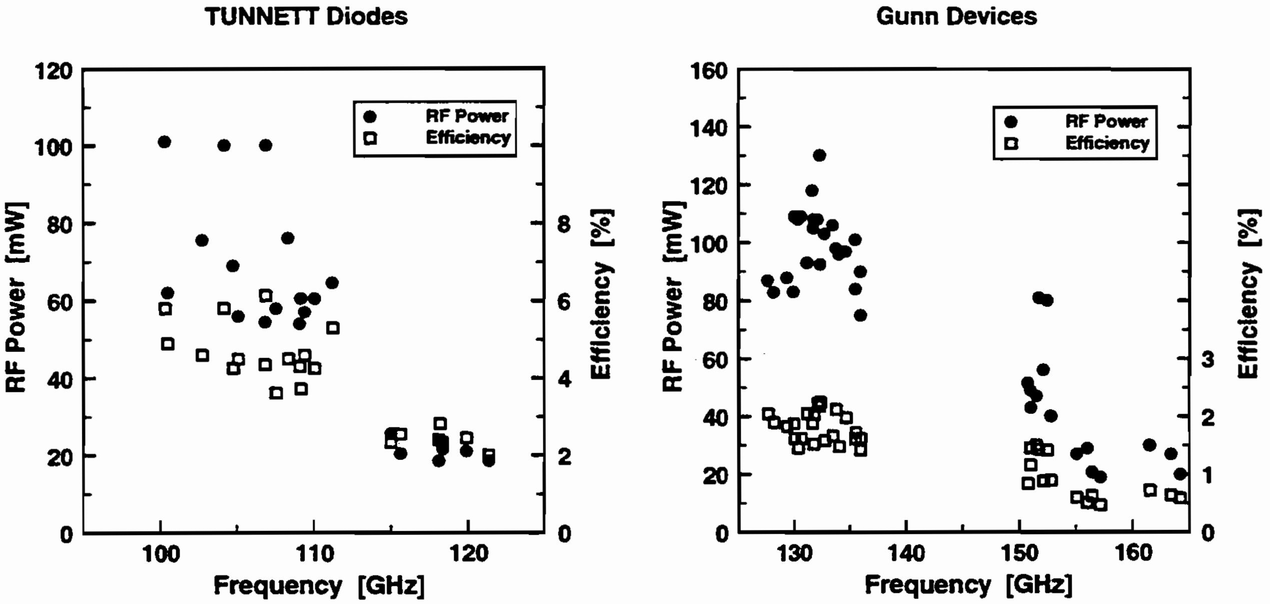

Figure 1: RF performance of GaAs TUNNETT diodes at W-band and InP Gunn devices at D-band frequencies, all on diamond heat sinks.

2. Experimental setups

All GaAs TUNNETT diodes were tested in the same type of a full-height WR-10 waveguide cavity as in fundamental-mode operation [1,3], where a resonant cap coarsely determined the oscillation frequency. A standard noncontacting back short for frequency and power fine-tuning was mounted on one flange of the cavity. Different configurations for reactively terminating the diode at the fundamental frequency were investigated. In all experiments with TUNNETT diodes and Gunn devices, a 1-inch-long WR-3 waveguide section cut off all signals below 173 GHz, which includes the signal at the fundamental frequency. Examples of configurations for TUNNETT diode oscillators are a tapered transition from the WR-10 waveguide of the cavity to the WR-3 waveguide or a discontinuity with a step from the WR-10 to the WR-3 waveguide. The configuration shown in Figure 2 resulted in the highest RF power levels from all tested TUNNETT diode oscillators. A tapered transition from the WR-6 to the WR-3 waveguide was connected directly to the WR-10 waveguide output flange of the cavity and introduced a small step discontinuity at this flange.

Most of the InP Gunn devices were tested in the same type of a full-height WR-6 waveguide cavity as in fundamental-mode operation [2,3], where, similar to the cavity for TUNNETT diodes, a resonant cap coarsely determined the oscillation frequency. Gunn devices in this type of cavity yielded the highest RF power levels with a sharp discontinuity from the WR-6 waveguide output flange to the WR-3 waveguide. For the experiments with the InP Gunn devices, also a scaled version of a Carlstrom-type [5] cavity with coaxial-line frequency short, a power back short in a WR-5 waveguide and a transition to the output WR-6 waveguide [6] was successfully employed.

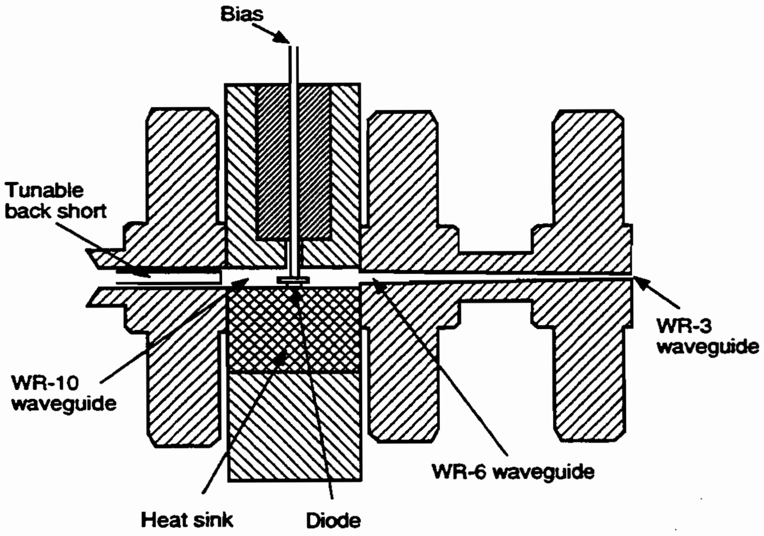

Figure 2: Schematic of the WR-10 waveguide cavity and waveguide transition for second-harmonic power extraction from GaAs TUNNETT diodes.

At first, a 140-220-GHz power sensor in a WR-5 waveguide or a D-band thermistor power meter with a WR-6 waveguide input flange was used to measure the RF power levels. Their sufficiently fast response time (compared to that of a calorimeter) allowed tracking of power changes quickly as the back short was tuned for maximum RF output power at the second-harmonic frequency. Tapered transitions from the WR-5 to WR-4 and WR-4 to WR-3 waveguides or from the WR-6 to WR-3 waveguide provided adequate impedance matching in the WR-3 waveguide at the second-harmonic frequency. Subsequently, a submillimeter-wave dry calorimeter with a WR-8 waveguide input flange and two tapered transitions, one from the WR-8 to WR-6 waveguide and the other from the WR-6 to WR-3 waveguide, each approximately 1-inch-long, was employed to confirm the RF power levels. An attenuation of 0.85 dB, for example, was measured at 234 GHz for the 1-inch-long WR-3 waveguide section in the setups, which is slightly higher than the predicted attenuation for a gold-plated waveguide. As a consequence, an attenuation of 0.55 dB was estimated for the two waveguide transitions to the calorimeter. The attenuation in either the WR-6 to WR-3 or the WR-10 to WR-3 waveguide transition at the oscillator output flange was not factored in in any of the experiments as such a transition was considered part of the oscillator circuit.

3. Experimental results

The measurements with the dry calorimeter verified all RF power levels from the TUNNETT diodes except for one result with an RF output power of more than 10 mW at 209 GHz. This minor discrepancy is attributed to changes that were introduced as oscillators were partly disassembled and reassembled between the measurements with power sensor or thermistor head and the measurements with the calorimeter. As a result, the conditions for generation of the RF power of more than 10 mW could not be reproduced. Figure 3 summarizes the best results measured with the calorimeter. As examples, RF power levels up to 9 mW and more than 4 mW were measured at second-harmonic frequencies of 209 GHz and 235 GHz, respectively, which correspond to dc-to-RF conversion efficiencies of more than 1.0 % and more than 0.6 %. Contrary to operation in the fundamental mode at 104-118 GHz, bias currents for optimum second-harmonic power extraction were in the range from 60 % to 85 % of the respective maximum bias currents. Therefore, operating junction temperatures were estimated [1] to be well below 150 °C, and reliable long-term operation can be expected from these diodes. As a further consequence, up-conversion efficiencies, which were determined as the ratios of RF power generated in a second-harmonic mode to RF power generated in the fundamental mode at the same bias current and fundamental oscillation frequency, always exceeded 9 % and were more than 20 % for the best results at 209 GHz and 235 GHz.

Second-harmonic power extraction with a Gunn device in Rydberg's cavity [6] yielded RF power levels of more than 2 mW at various frequencies between 220 GHz and 223 GHz as measured with the calorimeter. Tuning of the frequency short appeared to be critical since the cavity supported fundamental-mode operation of the same device very easily at numerous D-band frequencies around, *e.g.*, 150 GHz, but was not designed for efficient second-harmonic power extraction around, *e.g.*, 300 GHz. Furthermore, resulting RF power levels in the fundamental mode turned out to be below well-established state-of-the-art results from the same batch of InP Gunn devices [2,3] and, as a matter of fact, fundamental-mode operation was not within the scope of this work. Therefore, this mode of operation had to be avoided in this cavity.

RF power levels of 0.7 mW at 269 GHz, 1 mW at 279 GHz, and 1.2 mW at 280 GHz were obtained from InP Gunn devices in the WR-6 waveguide cavity and measured with the calorimeter. These RF power levels and those from the GaAs TUNNETT diodes are the highest reported to date for any other Gunn device and any GaAs transit-time diode, respectively. Second-harmonic RF power levels from the TUNNETT diodes and corresponding dc-to-RF conversion efficiencies, in particular, compare favorably with high-efficiency frequency multipliers, where Schottky varactor diodes are driven by low-noise Gunn device oscillators [7,8]. Lower than expected RF power levels from the Gunn devices in a second-harmonic mode indicate that optimum embedding impedances as seen by the diode at the fundamental and second-harmonic frequency have not yet been fully established.

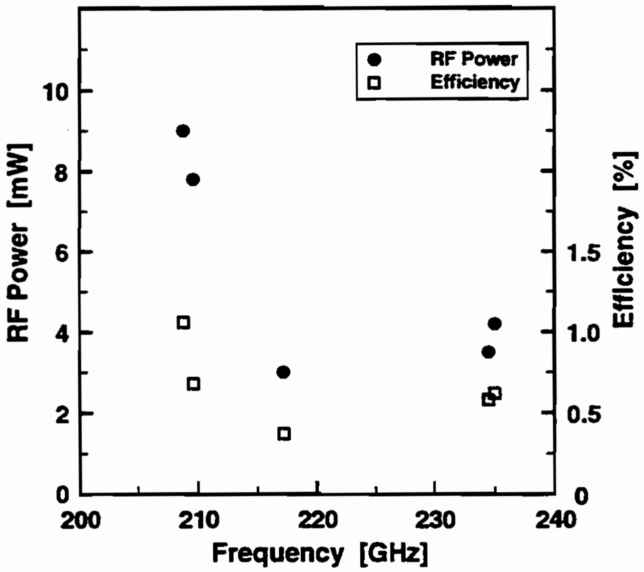

Figure 3: RF performance of GaAs single-drift TUNNETT diodes in a second-harmonic mode for the frequency range 200-240 GHz.

The spectra of free-running oscillators with Rydberg's cavity [6] and with all tested TUNNETT diodes in a WR-10 waveguide cavity were recorded at significant RF power levels by disconnecting the calorimeter and connecting a harmonic mixer to the WR-3 waveguide section. The phase noise determined at a frequency off the carrier of 500 kHz typically remained below - 87 dBc/Hz and was always at or below the noise floor of the employed spectrum analyzer and harmonic mixer. Therefore, actual phase noise levels were estimated to be considerably lower and correctly reflected the excellent noise performance known already from fundamental-mode operation [1-4]. Figure 4 shows an exemplary spectrum with a phase noise of < - 94 dBc/Hz at a frequency off the carrier of 500 kHz for the TUNNETT diode that yielded the RF power of 9 mW at a second-harmonic frequency of 209 GHz. Operation at a higher harmonic number causes much higher conversion loss in the harmonic mixer of the spectrum analyzer and prevents meaningful phase noise measurements for Gunn devices tested in the WR-6 waveguide cavity above 260 GHz.

4. Device simulations

Accurate predictions from diode simulations typically require prior knowledge of the embedding impedances seen by the diode at the frequencies of interest. However, GaAs TUNNETT diodes terminated with a matched load at the fundamental frequency were operated at 20-25 % lower bias voltages than measured without RF oscillations at the same maximum bias currents [9]. As shown in Figure 5 for a fundamental frequency of 107 GHz, this strong back bias effect reflects RF voltage amplitudes of 6.5-7.0 V, which were predicted by a large-signal simulation program [10]. This simulation program uses a two-valley energy-momentum model for electrons and a drift-diffusion model for holes, takes interband tunneling into account and was described in greater detail elsewhere [10]. Predicted RF power levels for fundamental-mode operation at the above-mentioned RF voltages and corresponding dc-to-RF conversion efficiencies including those of Figure 5 agree well with the experimental results of Figure 1.

For second-harmonic power extraction, the diodes were terminated mainly reactively at the fundamental frequency. At the RF power levels of Figure 3 and optimum bias current densities of 60-85 % of the maximum values in fundamental-mode operation, 25-30 % lower bias voltages than those without RF oscillations were observed and corresponded to predicted RF voltages of 7.0-8.0 V. Such large voltage swings are similar to those in second-harmonic transferred-electron devices, and, as illustrated with Figure 6, result in waveforms with a relatively sharp turn-on and a higher harmonic content of the current densities injected into the drift region of the diode than in the fundamental mode. Since RF voltages at the second-harmonic frequency were always less than 15 % of those at the fundamental frequency, no significant impact on the back bias effect could be observed in the simulations. In Figure 7, the electric field profiles in the active region of the diode are plotted for phases $\omega t = 0°$, 90°, 180°, and 270°, whereas the inset shows the three waveforms of the RF voltage across the diode, the injected and the total current densities of the diode as a function of time for one RF cycle at a fundamental frequency of 104 GHz. The bias current density was set to 35 kAcm^{-2}, and RF voltage amplitudes were adjusted to 7.3 V at 104 GHz and 0.6 V at 208 GHz.

As can be seen from Figure 7, the drift region shown as the n$^-$ region in the inset becomes nearly undepleted and neutral when the RF voltage approaches its minimum. When the RF voltage rises again and more of the drift region becomes depleted, a steep increase in the total current density ensues and corresponds to a high harmonic content. This large modulation of the depleted region in the diode resembles that of Schottky varactor diodes in high-efficiency frequency multipliers and explains the observed up-conversion efficiencies in excess of 20 % much better than just a sharp turn-on in the injected current density. All the above simulations took a total specific series resistance from ohmic contacts of $1.5 \times 10^{-6}\ \Omega\text{cm}^2$ into account and indicated that the RF output power at the second-harmonic strongly depends on the termination at the fundamental frequency, but is a relatively weak function of the impedance at the second-harmonic frequency. The simulations for Figures 6 and 7 predicted an RF output power of 16 mW with a corresponding dc-to-RF conversion efficiency of 1 % for a load impedance of $(1.5 + j\,4.0)\ \Omega$ at 208 GHz. These predicted values agree very well with the measured results of Figure 3.

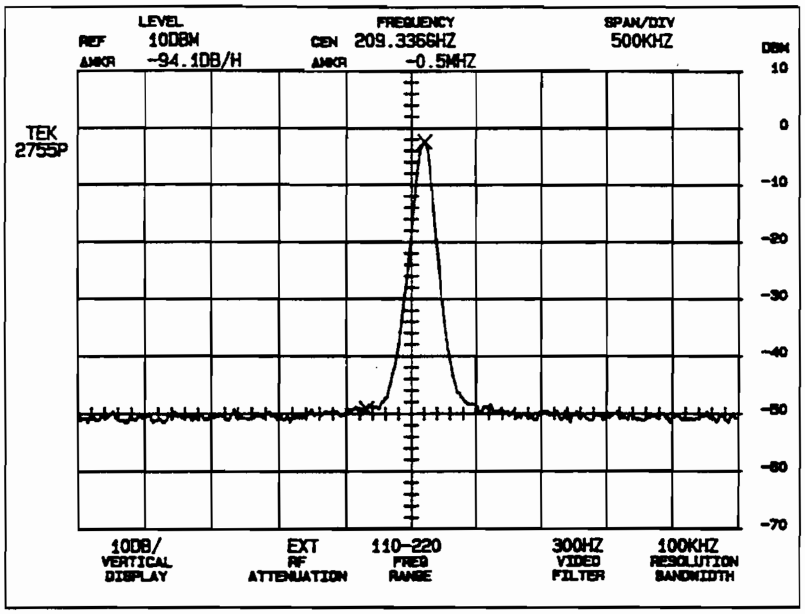

Figure 4: Spectrum of a free-running TUNNETT diode oscillator in a second-harmonic mode. RF power level 9 mW, center frequency 209.377 GHz, vertical scale 10 dB/div, horizontal scale 500 kHz/div, resolution bandwidth 100 kHz, video bandwidth 3 kHz.

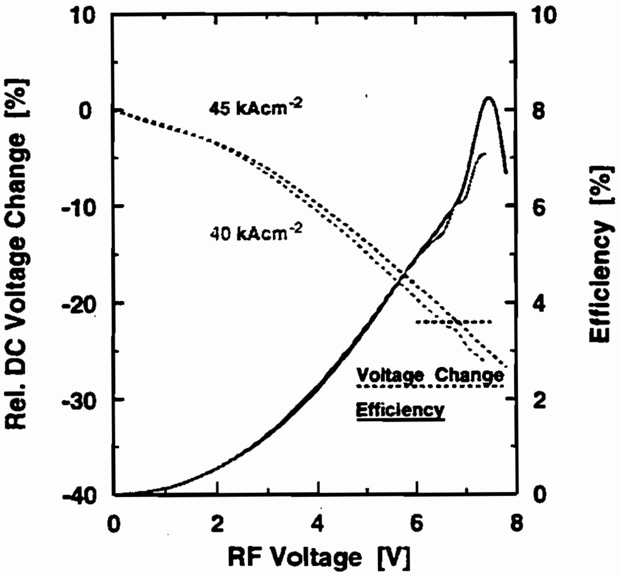

Figure 5: Predicted back bias effect and dc-to-RF conversion efficiency as a function of RF voltage amplitude for a GaAs TUNNETT diode in the fundamental mode at 107 GHz.

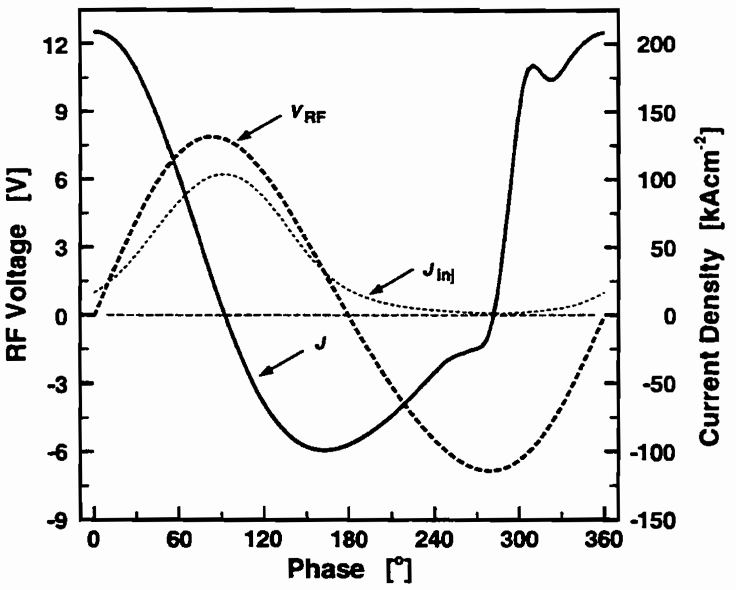

Figure 6: Waveforms of RF voltage V_{RF}, injected and total current densities J_{inj} and J of a GaAs TUNNETT diode as a function of time during one RF cycle at the fundamental frequency of 104 GHz.

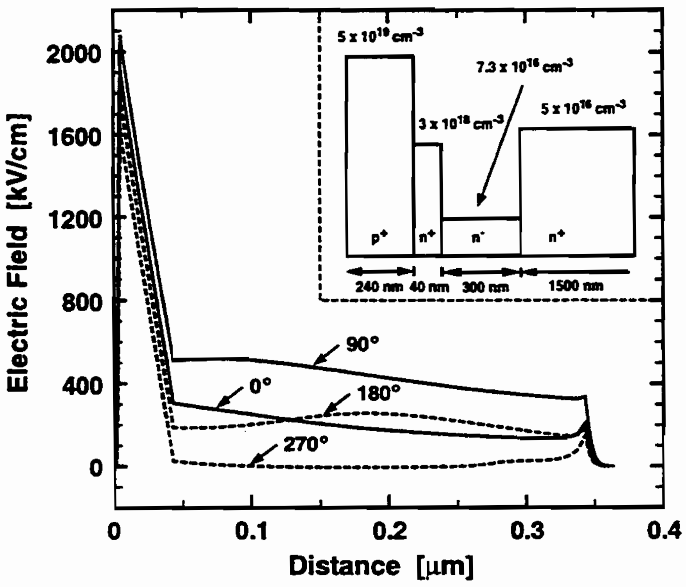

Figure 7: Electric field profiles of a GaAs TUNNETT diode in a second-harmonic mode at phases of 0°, 90°, 180°, and 270° during one RF cycle at the fundamental frequency of 104 GHz. Inset: Nominal doping profile of the TUNNETT diode.

5. Conclusion

Second-harmonic power extraction was demonstrated successfully with GaAs TUNNETT diodes and InP Gunn devices at frequencies above 200 GHz. To the author's knowledge, RF power levels up to 9 mW and dc-to-RF conversion efficiencies of more than 1 % are the highest reported to date from any GaAs transit-time diode, and RF power levels of more than 1 mW at 280 GHz are the highest reported to date from any GaAs or InP Gunn devices. In particular, results from GaAs TUNNETT diodes compare favorably with results from low-noise all-solid-state RF sources with frequency multipliers [7,8]. Simulations revealed a mode of operation similar to the large modulation in the width of the depleted region as seen in Schottky varactor diodes. Therefore, the high up-conversion efficiencies observed are attributed much more to this large capacitance modulation of the diode than to a high harmonic content in the injected and the resulting induced diode currents. Performance parameters predicted for TUNNETT diodes agree well with measured results. In InP Gunn devices, the interaction of circuit and device, *i.e.*, the impedance levels at the fundamental and the second-harmonic frequencies, must be studied in greater detail to increase the RF power levels that can be extracted in a second-harmonic mode.

Acknowledgment

Thanks go to Anders Rydberg at the University of Uppsala for making the cavity available as well as to Imran Mehdi with the Jet Propulsion Laboratory and Michael Coulombe with the University of Massachusetts at Lowell for providing the submillimeter-wave power meter and calorimeter, respectively.

References

[1] Eisele, H., Haddad, G. I.: "Enhanced Performance in GaAs TUNNETT Diode Oscillators Above 100 GHz Through Diamond Heat Sinking and Power Combining", *IEEE Transactions on Microwave Theory and Techniques*, **MTT-42**, 1994, pp. 2498-2503.

[2] Eisele, H., Haddad, G. I.: "High-Performance InP Gunn Devices for Fundamental-Mode Operation in D-Band (110-170 GHz)", *IEEE Microwave and Guided Wave Letters*, **MWGL-5**, 1995, pp. 385-387.

[3] Eisele, H., Haddad, G. I.: "Two-Terminal Millimeter-Wave Sources", to appear in *IEEE Transactions on Microwave Theory and Techniques*, **MTT-46**, 1998.

[4] Eisele, H., Haddad, G. I.: "D-Band InP Gunn Devices with Second-Harmonic Power Extraction up to 290 GHz", *Electronics Letters*, **30**, 1994, pp. 1950-1951.

[5] Carlstrom, J. E., Plambeck, R. L., Thornton, D. D.: "A Continuously Tunable 65-115-GHz Gunn Oscillator", *IEEE Transactions on Microwave Theory and Techniques*, **MTT-33**, 1985, pp. 610-619.

[6] Rydberg, A.: "High Efficiency and Output Power from Second- and Third-Harmonic Millimeter-Wave InP-TED Oscillators at Frequencies above 170 GHz", *IEEE Electron Device Letters*, **EDL-11**, 1990, pp. 439-441.

[7] Räisäinen, A. V.: "Frequency Multipliers for Millimeter and Submillimeter Wavelengths", *Proceedings of the IEEE*, **80**, 1992, pp. 1842-1852.

[8] Crowe, T. W., Grein, T. C., Zimmermann, R., Zimmermann, P.: "Progress Toward Solid-State Local Oscillators at 1 THz", *IEEE Microwave and Guided Wave Letters*, **MWGL-6**, 1996, pp. 207-208, **and**, Crowe, T. W., Grein, T. C., Zimmermann, R., Zimmermann, P.: Correction to "Progress Toward Solid-State Local Oscillators at 1 THz", *IEEE Microwave and Guided Wave Letters*, **MWGL-6**, 1996, pp. 383.

[9] Eisele, H., Chen, C-C., Mains, R. K., Haddad, G. I.: "Performance of GaAs TUNNETT Diodes as Local Oscillator Sources", *Proceedings of the Fifth International Symposium on Space Terahertz Technology*, May 10 - May 13, 1994, Ann Arbor, Michigan, pp. 622-628.

[10] Chen, C-C., Mains, R. K., Haddad, G. I., Eisele, H.: "Numerical Simulation of TUNNETT and MITATT Devices in the Millimeter and Submillimeter Range", *Proceedings of the Fourth International Symposium on Space Terahertz Technology*, March 30 - April 1, 1993, Los Angeles, California, pp. 362-376.