Recent Advances in the Performance of InP Gunn Devices and GaAs TUNNETT Diodes for the 100–300-GHz Frequency Range and Above

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***Abstract*—Improved heat dissipation in InP Gunn devices resulted in RF power levels exceeding 200, 130, 80, and 25 mW at oscillation frequencies of around 103, 132, 152, and 162 GHz, respectively. Corresponding dc-to-RF conversion efficiencies exceeded 2.3% from 102 to 132 GHz. Power combining increased the available RF power levels to over 300 mW at 106 GHz, around 130 mW at 136 GHz, and more than 125 mW at 152 GHz with corresponding combining efficiencies from 80% to over 100%. Operation in a second harmonic mode yielded RF power levels of more than 3.5 mW at 214 GHz, over 2 mW around 220 GHz as well as over 1 mW around 280, 300, and 315 GHz. RF power levels exceeding 10 mW at 202 GHz, 9 mW around 210 GHz, and 4 mW around 235 GHz were obtained from GaAs TUNNETT diodes in a second harmonic mode as well. Corresponding dc-to-RF conversion efficiencies were around 1% at 202 and 210 GHz.**

***Index Terms*—Gunn devices, IMPATT diodes, millimeter-wave devices, millimeter-wave generation, millimeter-wave oscillators, oscillator noise, phase noise, submillimeter-wave devices, submillimeter-wave generation, submillimeter-wave oscillators, transit-time diodes.**

I. Introduction

COMPACT and sensitive submillimeter-wave receivers largely depend on low-noise all-solid-state local oscillators (LO's), where a frequency multiplier or a chain of multiplier stages driven with a high-power Gunn device as the fundamental source has been the most common approach [1], [2]. High-power fundamental sources are necessary to provide sufficient LO power at terahertz frequencies [2], e.g., to pump uncooled Schottky diode mixers subharmonically [3]. As more RF power at higher millimeter- or even submillimeter-wave frequencies becomes available from Gunn devices or tunnel injection transit-time (TUNNETT) diodes as the fundamental sources, the number of required multiplier stages and, consequently, the complexity of the LO chain decrease.

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Device simulations [4] and preliminary experimental results [5] from devices on integral heat sinks indicated thermal limitations in InP Gunn devices, in particular, at D-band (110–170 GHz) frequencies. Therefore, fabrication technologies based on selective etching were adopted from previously developed processes for GaAs impact avalanche transit-time (IMPATT) [6] and TUNNETT [7] diodes on diamond heat sinks, and resulting InP Gunn devices were mounted on diamond heat sinks in an open package with reasonably low parasitic elements. This paper describes the RF performance of InP Gunn devices with different doping profiles as single devices in the fundamental mode, as well as those employed in power-combining circuits and in circuits for second harmonic power extraction. GaAs TUNNETT diodes on diamond heat sinks already displayed quite useful RF power levels and dc-to-RF conversion efficiencies around 100 GHz [7], [8] and, as a consequence of their strongly nonlinear properties, are another good candidate for second harmonic power extraction. The most recent results from this method of generating RF power are also included in this paper.

II. Performance of Single InP Gunn Devices

Improved fabrication technologies as well as a better understanding of both the physics in transferred-electron devices (TED's) [4], [9], [10] and some of the limitations in InP Gunn devices resulted in the extension of fundamental-mode operation beyond 160 GHz [5], [10]. As shown in Fig. 1, RF power levels exceeding 130 mW around 132 GHz, 80 mW around 152 GHz, and 25 mW around 162 GHz were achieved with devices on diamond heat sinks [10]. These RF power levels represent a more than fourfold performance improvement compared to devices on integral heat sinks,[1] which were fabricated from the same epitaxial material and evaluated in the same WR-6 waveguide cavities. RF power levels of 15–18 mW were measured around 133 GHz with devices that had the cathode close to the heat sink [5] as well as 20–26 mW at 130–135 GHz with devices where the anode was close to the heat sink.[1] Low heat-flow resistances on diamond heat sinks [10] ensure low active-layer temperatures for reliable long-term operation. No signs of appreciable degradation or change in oscillation frequency were observed during continuous-wave (CW) operation for over 15 000 h of one device around 131 GHz. At a typical

[1]Unpublished results of H. Eisele.

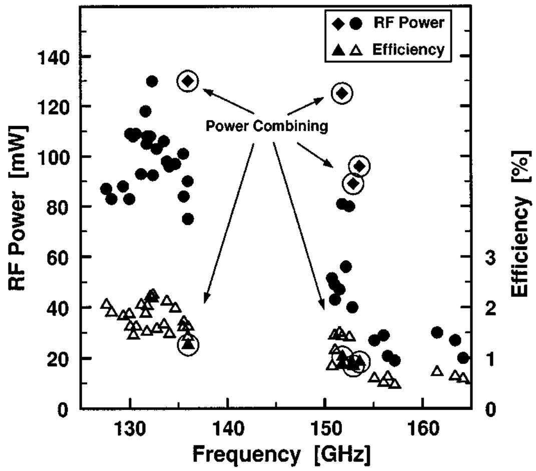

Fig. 1. RF performance of InP Gunn devices on diamond heat sinks at D-band frequencies (epitaxial material grown by MOCVD).

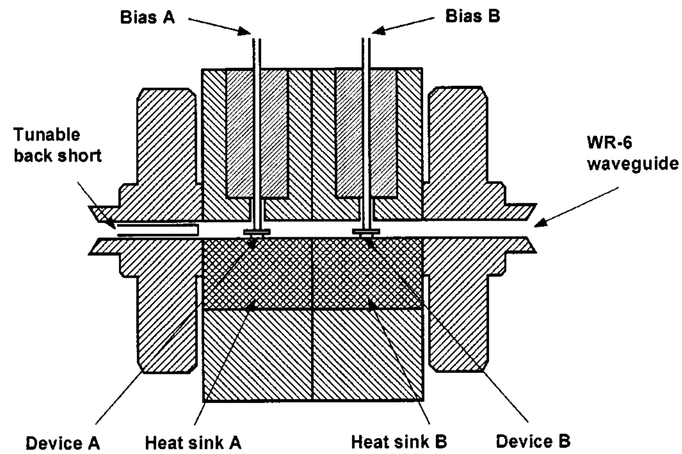

Fig. 2. Schematic of the WR-6 waveguide circuit for InP Gunn device power combining at D-band frequencies.

power stability against temperature of better than -0.04 dB/°C, the observed fluctuations in the recorded RF power levels of within ±5% were largely attributed to inevitable changes in the ambient temperature of the laboratory space with the test setup.

As a well-known characteristic of Gunn devices, one device structure can generate RF output power over a wide frequency range. Lowest and highest frequency limits of devices with the graded doping profile [10] have not yet been determined as part of a detailed investigation. Nonetheless, the employed device evaluation procedure [10] typically covers more than one waveguide band. It revealed in some devices that, with the same device in an appropriate cavity and RF circuit, significant RF power levels could be generated easily at any frequency in the range from below 94 GHz to above 155 GHz. An RF power of over 200 mW was measured with one of these devices in a WR-10 waveguide cavity at an oscillation frequency of 103 GHz.

Material from different epitaxial growth systems, such as, metalorganic chemical vapor deposition (MOCVD) and chemical beam epitaxy (CBE), but also molecular beam epitaxy (MBE), was and is being used with success in the performance studies. As one example, D-band InP Gunn devices on diamond heat sinks with a flat doping profile and from CBE-grown material yielded RF power levels of around 100 mW at oscillation frequencies of around 130 GHz [11]. Other examples are results from W-band devices that had comparable flat doping profiles and were fabricated from either MBE- or CBE-grown material. These devices on integral heat sinks were operated in the fundamental mode and generated RF power levels of 30–45 mW in the 101–108-GHz frequency range.[2] Further examples are results from devices again with a flat doping profile and on integral heat sinks, but operated in a second harmonic mode, which is discussed in Section V.

Clean spectra were recorded from the vast majority of the Gunn devices tested as free-running oscillators. As an example, an uncorrected phase noise of -110 dBc/Hz was determined at 500 kHz off the oscillation frequency of 103 GHz and at an RF power of 180 mW, which is in line with previously reported values of well below -100 dBc/Hz at D-band frequencies [10]–[12]. Since the phase noise is at the noise floor of the employed spectrum analyzer with a harmonic mixer, the corrected phase noise is estimated to be well below -113 dBc/Hz.

III. Power Combining with InP Gunn Devices

Power combining of two devices was demonstrated for the first time [13] in the fundamental mode at D-band (110–170 GHz) frequencies, but was also shown to result in state-of-the-art RF power levels at W-band (75–110 GHz) frequencies. Excellent combining efficiencies from 80% to over 100% were achieved in the simple dual-cavity in-line configuration, as illustrated in Fig. 2. Fig. 1 also includes more recent results from additional power-combining experiments. The highest RF power levels to date exceeded 300 mW at 106 GHz and 125 mW at 152 GHz and were around 130 mW at 136 GHz. Recorded spectra were very clean, and phase-noise characteristics were very similar to those reported for single devices in free-running oscillators [10]–[12].

IV. Second Harmonic Power Extraction from GaAs TUNNETT Diodes

A strong back bias effect [14] and preliminary RF measurements [7] indicated strongly nonlinear properties in GaAs TUNNETT diodes. In subsequent experiments, different configurations for the transition from the WR-10 waveguide of the cavity to the WR-3 output waveguide were investigated. The WR-3 waveguide with a cutoff frequency of 173 GHz is necessary to inhibit propagation of RF signals at the fundamental frequency. Conversely, the signal at the fundamental frequency can still propagate in a WR-6 waveguide. As a result, the WR-6 to WR-3 waveguide transition, as shown in Fig. 3, introduces a step discontinuity at the WR-10 waveguide output flange for signals at the fundamental as well as harmonic frequencies. Among all transitions investigated, this transition resulted in the best performance from all tested diodes. Second harmonic power extraction was obtained up to 237 GHz and, as shown in Fig. 4, RF power levels of over 10 mW at 202 GHz, over 9 mW around

[2]Unpublished results of H. Eisele.

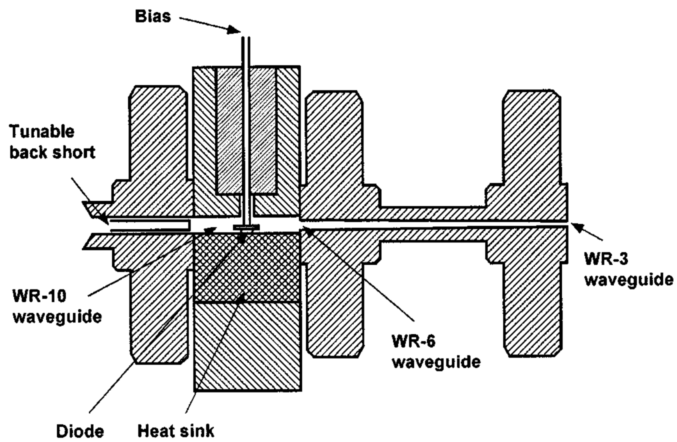

Fig. 3. Schematic of the waveguide circuit for second harmonic power extraction from GaAs TUNNETT diodes.

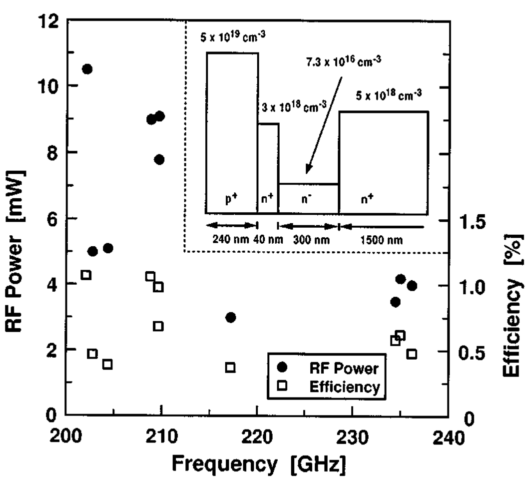

Fig. 4. RF performance of GaAs TUNNETT diodes in a second harmonic mode above 200 GHz. Inset: nominal doping profile of the TUNNETT diode.

210 GHz, and over 4 mW around 235 GHz were measured with a submillimeter-wave dry calorimeter [15].

Spectra were recorded from all diodes tested at significant RF power levels as free-running oscillators. They appeared to be very clean, and, as an example, an uncorrected phase noise of −94 dBc/Hz was determined at 500 kHz off the oscillation frequency of 209.377 GHz and at an RF power of 9 mW [16]. This phase noise correctly reflects previously reported values of well below −94 dBc/Hz in the fundamental mode at W-band frequencies [7], [8]. Since the phase noise is at the noise floor of the employed spectrum analyzer with a harmonic mixer, the corrected phase noise is estimated to be well below −98 dBc/Hz.

The dc power consumption of the diodes of Fig. 4 ranged from approximately 0.6 to 1.3 W and typically remained well below 1 W. Consequently, operating junction temperatures were estimated [7] to be well below 125 °C and typically around 100 °C, which ensures reliable long-term operation even at cavity temperatures above 25 °C.

DC-to-RF conversion efficiencies of around 1% are among the highest reported to date for any fundamental solid-state RF source in the 200–220-GHz frequency range. As diode simula-

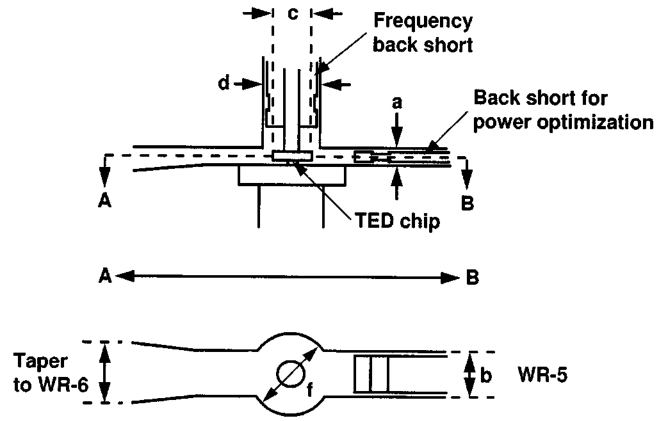

Fig. 5. Schematic of the WR-5/6 waveguide circuit for second harmonic power extraction in the 140–220-GHz frequency range, shown for the case of an unpackaged InP Gunn device.

tions revealed, these efficiencies result from a mode of operation akin to Schottky varactors in high-performance frequency multipliers. During one RF cycle at the fundamental frequency, the drift region, which is the n^--doped region in the inset of Fig. 4, is first filled up with electrons and becomes largely undepleted, then subsequently is almost completely swept free of carriers. This large modulation in the depleted width (space charge region) enhances the harmonic power generation. An RF output power of 16 mW is predicted to be delivered to a load impedance $\underline{Z}_L$ of $(1.5 + j4.0)\Omega$ at 208 GHz [16], [17], which corresponds to a dc-to-RF conversion efficiency of 1% and also agrees well with the experimental results of Fig. 4.

V. Second Harmonic Power Extraction from InP Gunn Devices

Millimeter-wave GaAs and InP Gunn devices are better known for efficient operation in a second harmonic mode [9], [18] than GaAs TUNNETT diodes, and this mode has been exploited in many system applications up to D-band. In the present study, different circuit configurations were explored for efficient second harmonic power extraction above W-band. A scaled version of a Carlstrom-type cavity [19] was employed for experiments in G-band (140–220 GHz). Fig. 5 shows a schematic of this waveguide circuit [20], [21]. In this circuit, the coaxial section, which can be tuned with the frequency back short, basically forms a resonant circuit at the fundamental frequency with the device capacitance, the fringe capacitance of the cap on the device, and, if present, the parasitic elements of the device package. The WR-5 reduced-height waveguide section of the cavity has a cutoff frequency f_c of 115 GHz and, therefore, the signal at the appropriate fundamental frequency below f_c cannot propagate. As a result, the device is mainly reactively terminated at the fundamental frequency, which causes a large voltage swing in the highly nonlinear device and generation of higher harmonic frequencies [18], [21].

At first, devices on integral heat sinks were evaluated for second harmonic power extraction in this cavity. These devices were designed for fundamental-mode operation at W-band frequencies, had flat doping profiles similar to those in [4], and

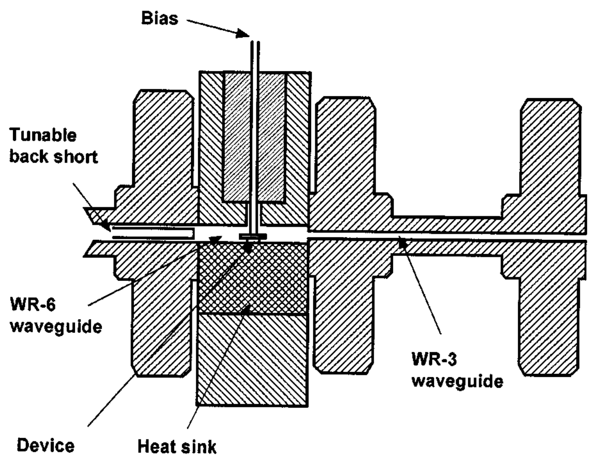

Fig. 6. Schematic of the waveguide circuit for second harmonic power extraction from InP Gunn devices in the 260–320-GHz frequency range.

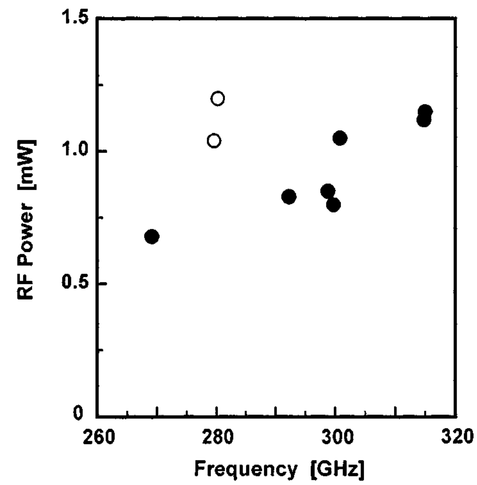

Fig. 7. RF performance of InP Gunn devices on diamond heat sinks in a second harmonic mode in the 260–320-GHz frequency range. •: anode close to the heat sink. ○: cathode close to the heat sink.

were fabricated from CBE-grown material. RF power levels of over 10 mW at approximately 150–165 GHz and over 5 mW around 170 GHz were measured and are comparable to values reported previously [19] for devices from MOCVD-grown material [22]. As a result of the resonant cap on top of the device, the cavity also supports fundamental-mode operation above the cutoff frequency of the WR-5 waveguide. For example, some flat-profile devices on integral heat sinks yielded up to 18 mW around 131 GHz, where low bias voltages and significant frequency tuning with the power back short position in the WR-5 waveguide indicated fundamental-mode operation.

Subsequently, a D-band device on a diamond heat sink was inserted. As expected, operation at higher second harmonic frequencies was observed. The experiments yielded RF power levels of over 2 mW as measured with the submillimeter-wave dry calorimeter at various frequencies between 220–223 GHz. Tuning of the frequency short appeared to be critical since the devices easily oscillated in the fundamental-mode at numerous D-band frequencies around, e.g., 150 GHz, but the cavity 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 the well-established state-of-the-art results from the same batch of InP Gunn devices, as shown in Fig. 1, and, in fact, fundamental-mode operation was not within the scope of these experiments. As a consequence, this mode of operation had to be avoided in this cavity.

Very preliminary results up to 290 GHz from D-band devices on diamond heat sinks were reported [12] from the circuit configuration shown in Fig. 6, which is similar to that of Fig. 3 for TUNNETT diodes. Accurate models for two-terminal devices are prerequisite for tailoring the performance and optimizing the device structures. The accuracy of performance predictions was and is being improved by comparing predicted and measured characteristics and, e.g., by fine-tuning essential material parameters [4]. A comparative study of load impedance levels $\underline{Z}_L = R_L + jX_L$ at the optimum performance of millimeter-wave two-terminal devices[3] revealed that the imaginary part X_L invariably remains in the range of 4–10 Ω across different device types, such as GaAs IMPATT, MITATT, and TUNNETT diodes, as well as across different waveguide bands for the configuration of a full-height waveguide cavity with a resonant cap on top of the device. Devices with diameters for optimum performance in the fundamental-mode at D-band frequencies [10] require values of X_L at corresponding second harmonic frequencies in the range of 0.5–3 Ω, which is outside the above range and may explain unsatisfactory performance in a second harmonic mode and in the configuration of Fig. 6. As a consequence, devices with smaller diameters were selected and evaluated in greater detail.

As shown in Fig. 7, these experiments yielded RF power levels of 0.7 mW at 269 GHz, 1 mW at 279 GHz, 1.2 mW at 280 GHz, 1 mW at 300 GHz, and 1.1 mW at 315 GHz [23], which were measured with a submillimeter-wave dry calorimeter [15]. These RF power levels exceed early predictions of the capabilities of InP Gunn devices [18], [24].

Similar to the experiments with the TUNNETT diodes, the influence of the type of transition from the WR-6 waveguide to the WR-3 waveguide was also investigated experimentally. Contrary to the configuration for the TUNNETT diodes (see Fig. 3), the abrupt transition from the WR-6 waveguide of the cavity to the WR-3 waveguide yielded the best RF performance. However, in an experiment with a WR-10 waveguide cavity, a step discontinuity at the transition from the WR-4 to WR-3 waveguide appeared to be beneficial and increased the extracted RF power levels to over 3.5 mW at 213 GHz.

VI. Conclusion

As can be seen from Figs. 8 and 9, the best RF power levels in the 100–300-GHz frequency range are the highest reported to date for any Gunn device and any TUNNETT diode, respectively. However, the interaction between the circuit and device, i.e., the impedance levels at the fundamental and second harmonic frequencies, need to be studied in greater detail. This should lead to much improved performance from operation of Gunn devices in a second harmonic mode above 200 GHz, as

[3]Unpublished results of H. Eisele.

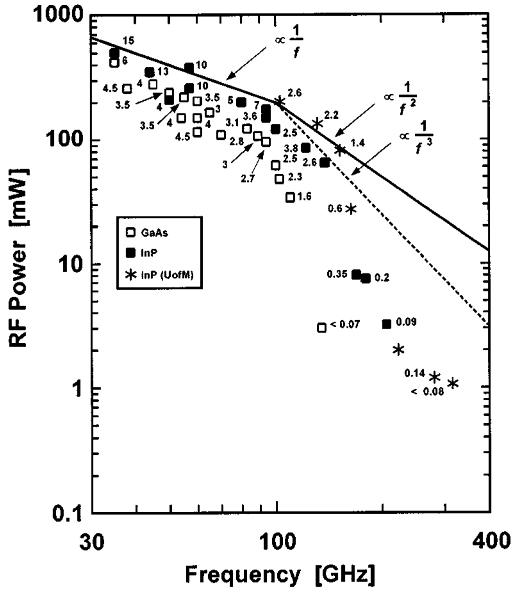

Fig. 8. Published state-of-the art results from GaAs and InP Gunn devices under CW operation in the frequency range of 30–400 GHz. Numbers next to the symbols denote dc-to-RF conversion efficiencies in percent.

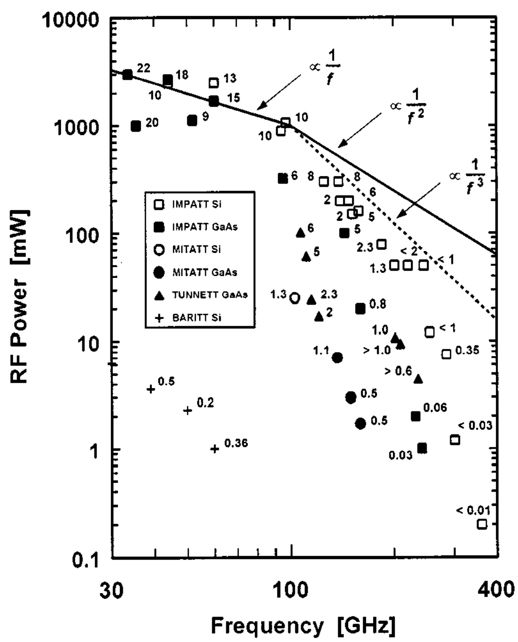

Fig. 9. Published state-of-the art results from Si and GaAs transit-time diodes under CW operation in the frequency range of 30–400 GHz. Numbers next to the symbols denote dc-to-RF conversion efficiencies in percent.

predicted by a number of different device simulations [18], [24], [25]. Higher RF power levels and oscillation frequencies can also be expected from TUNNETT diodes designed appropriately with shorter drift regions and for operation at higher current densities.

As also illustrated in Fig. 9, Si IMPATT diodes had been the only solid-state device thus far where RF power levels of over 1 mW were reported for oscillators in CW operation above Y-band (170–260 GHz). Exemplary RF power levels (and corresponding dc-to-RF conversion efficiencies) of 50 mW (1.3%) at 202 GHz [26], 44 mW (1.2%) at 214 GHz [26], 50 mW (<2%) at 217 GHz [27], 50 mW (<1%) at 245 GHz [27], 12 mW (<0.5%) at 255 GHz [27], 7.5 mW (0.35%) at 285 GHz [28], 1.2 mW (<0.05%) at 301 GHz [26], and 0.2 mW at 361 GHz [28] were measured at very high operating junction temperatures (>300 °C) with waveguide circuits at room temperature. Higher RF power levels were attained by cooling the waveguide circuit to 77K (liquid N_2) and 4.5 mW (0.13%) at 295 GHz, 2.2 mW (0.047%) at 412 GHz were reported [29]. As a consequence, the InP Gunn devices on diamond heat sinks are the most powerful solid-state fundamental RF source operated at room temperature and for frequencies above 300 GHz, whereas GaAs TUNNETT diodes are the second most powerful solid-state fundamental RF source operated at room temperature and for frequencies above 200 GHz.

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REFERENCES

[1] A. V. Räisäinen, "Frequency multipliers for millimeter and submillimeter wavelengths," *Proc. IEEE*, vol. 80, pp. 1842–1852, Nov. 1992.

[2] T. W. Crowe, T. C. Grein, R. Zimmermann, and P. Zimmermann, "Progress toward solid-state local oscillators at 1 THz," *IEEE Microwave Guided Wave Lett.*, vol. 6, pp. 207–208, May 1996.

[3] I. Mehdi, P. H. Siegel, D. A. Humphrey, T. H. Lee, R. J. Dengler, J. E. Oswald, A. Pease, R. Lin, H. Eisele, R. Zimmermann, and N. Erickson, "An all solid-state 640 GHz subharmonic mixer," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Baltimore, MD, June 7–12, 1998, pp. 403–406.

[4] R. Kamoua, H. Eisele, and G. I. Haddad, "D-band (110-170 GHz) InP Gunn devices," *Solid State Electron.*, vol. 36, pp. 1547–1555, 1993.

[5] H. Eisele, R. Kamoua, G. I. Haddad, and C. Kidner, "Active two-terminal devices as local oscillators for low-noise receiver systems at submillimeter-wave frequencies," *Arch. Elektrotech.*, vol. 77, pp. 15–19, 1994.

[6] H. Eisele, "Selective etching technology for 94-GHz GaAs IMPATT diodes on diamond heat sinks," *Solid State Electron.*, vol. 32, pp. 253–257, 1989.

[7] H. Eisele and G. I. Haddad, "Enhanced performance in GaAs TUNNETT diode oscillators above 100 GHz through diamond heat sinking and power combining," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 2498–2503, Dec. 1994.

[8] ——, "Two-terminal millimeter-wave sources," *IEEE Trans. Microwave Theory Tech.*, vol. 46, pp. 739–746, June 1998.

[9] ——, "Active microwave diodes," in *Modern Semiconductor Device Physics*, S. M. Sze, Ed. New York: Wiley, 1997, ch. 6, pp. 343–407.

[10] ——, "High-performance InP Gunn devices for fundamental-mode operation in D-band (110–170 GHz)," *IEEE Microwave Guided Wave Lett.*, vol. 5, pp. 385–387, Nov. 1995.

[11] H. Eisele, G. O. Munns, and G. I. Haddad, "RF performance characteristics of InP millimeter-wave n^+-n^--n^+ Gunn devices," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Denver, CO, June 17–21, 1997, pp. 451–454.

[12] H. Eisele and G. I. Haddad, "D-band InP Gunn devices with second-harmonic power extraction up to 290 GHz," *Electron. Lett.*, vol. 30, pp. 1950–1951, 1994.

[13] ——, “Efficient power combining with D-band (110-170 GHz) InP Gunn devices in fundamental-mode operation,” *IEEE Microwave Guided Wave Lett.*, vol. 8, pp. 24–26, Jan. 1998.

[14] ——, “GaAs TUNNETT diodes on diamond heat sinks for 100 GHz and above,” *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 210–213, Jan. 1995.

[15] N. R. Erickson and J. Tuovinen, “A waveguide tripler for 720–880 GHz,” in *Proc. 6th Int. Space Terahertz Technol. Symp.*, Pasadena, CA, Mar. 21-23, 1995, pp. 191–198.

[16] H. Eisele, “Efficient second-harmonic power extraction from GaAs TUNNETT diodes above 200 GHz,” *Electron. Lett.*, vol. 34, pp. 1324–1326, 1998.

[17] ——, “Efficient second-harmonic power extraction from GaAs TUNNETT diodes above 200 GHz,” *Electron. Lett.*, vol. 34, p. 1531, 1998.

[18] I. G. Eddison, “Indium phosphide and gallium arsenide transferred-electron devices,” in *Infrared and Millimeter Waves*, ser. Millimeter Components and Techniques Part III. New York: Academic, 1984, vol. 11, pp. 1–59.

[19] J. E. Carlstrom, R. L. Plambeck, and D. D. Thornton, “A continuously tunable 65–115-GHz Gunn oscillator,” *IEEE Trans. Microwave Theory Tech.*, vol. 33, pp. 610–619, July 1985.

[20] A. Rydberg, “High efficiency and output power from second- and third-harmonic millimeter-wave InP-TED oscillators at frequencies above 170 GHz,” *IEEE Electron Device Lett.*, vol. 11, pp. 439–441, Oct. 1990.

[21] ——, “A contribution to the design of wide-band tunable second-harmonic mode millimeter-wave InP-TED oscillators above 110 GHz,” *Int. J. Infrared Millim. Waves*, vol. 11, pp. 383–404, 1990.

[22] M. A. di Forte-Poisson, C. Brylinski, G. Colomer, D. Osselin, S. Hersee, J. P. Duchemin, F. Azan, D. Lechevallier, and J. Lacombe, “High-power high-efficiency LP-MOCVD InP Gunn diodes for 94 GHz,” *Electron. Lett.*, vol. 20, pp. 1061–1062, 1984.

[23] H. Eisele, “Second-harmonic power extraction from InP Gunn devices with more than 1 mW in the 260–320 GHz frequency range,” *Electron. Lett.*, vol. 34, pp. 2412–2413, 1998.

[24] M. R. Friscourt and P. A. Rolland, “Optimum design of n^+-n-n^+ InP devices in the millimeter-range frequency limitation-RF performances,” *IEEE Electron Device Lett.*, vol. EDL-4, pp. 135–137, May 1983.

[25] R. Kamoua, “Potential of second-harmonic power generation in InP Gunn oscillators above 200 GHz,” in *Proc. 4th Int. Millimeter Submillimeter Waves Applicat. Conf.*, San Diego, CA, July 20–24, 1998, pp. 32–37.

[26] T. Ishibashi and M. Ohmori, “200-GHz 50-mW CW oscillation with silicon SDR IMPATT diodes,” *IEEE Trans. Microwave Theory Tech.*, vol. MTT-24, pp. 858–859, Nov. 1976.

[27] K. Chang, W. F. Thrower, and G. M. Hayashibara, “Millimeter-wave silicon IMPATT sources and combiners for the 110–260-GHz range,” *IEEE Trans. Microwave Theory Tech.*, vol. MTT-29, pp. 1278–1284, December 1981.

[28] M. Ino, T. Ishibashi, and M. Ohmori, “CW oscillation with p^+-p-n^+ silicon IMPATT diodes in 200 GHz and 300 GHz bands,” *Electron. Lett.*, vol. 12, pp. 148–149, 1976.

[29] T. Ishibashi, M. Ino, T. Makimura, and M. Ohmori, “Liquid-nitrogen-cooled submillimeter-wave silicon IMPATT diodes,” *Electron. Lett.*, vol. 13, pp. 299–300, 1977.

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