POWER GENERATION WITH IMPATT DIODES, TUNNETT DIODES AND GUNN DEVICES AT MILLIMETER AND SUBMILLIMETER WAVE FREQUENCIES

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Abstract:

Recent experimental results have shown that GaAs IMPATT diodes can operate up to D-band frequencies. RF output power levels of up to 20 mW at 120 GHz and 15 mW at 135 GHz were obtained. Corresponding dc to RF conversion efficiencies were between 0.9 % and 1.5 %. Device simulations and preliminary experimental results indicate that the fundamental mode operation of InP Gunn devices can be extended to the upper end of the D-band. RF output power levels of 21 mW were measured at 120 GHz, 17 mW at 133 GHz and 8 mW at 155 GHz. The most promising candidate for power generation at submillimeter wave frequencies, the TUNNETT diode, has yielded RF power levels of up to 35 mW around 103 GHz with corresponding dc to RF conversion efficiencies up to 3.5 %.

IMPATT diodes, TUNNETT diodes and Gunn devices exhibit clean spectra up to the highest oscillation frequencies, which makes them useful devices for local oscillator applications.

All these devices are strongly nonlinear. Therefore power extraction at higher harmonics was also investigated. Preliminary measurements were carried out in a non-optimized circuit of a full height waveguide cavity for the fundamental frequency with a resonant cap on top of the device. 0.12 mW at 182 GHz were obtained from a GaAs W-band IMPATT diode and 13 µW at 240 GHz from a GaAs D-band IMPATT diode both at the second harmonic. W-Band TUNNETT diodes at the second harmonic gave 40 µW at 200 GHz and 0.25 mW at 224 GHz. D-band Gunn devices yielded 0.4 mW at 220 GHz and 90 µW at 228 GHz.

1. Introduction

There is a growing need for local oscillator power above 100 GHz in radioastronomy. Although impressive progress has been demonstrated for oscillators with three-terminal devices at mm-wave frequencies [1,2] two-terminal devices still hold the greatest promise in delivering significant power levels at sub-mm-wave frequencies. This paper summarizes the recent experimental results obtained from IMPATT diodes, TUNNETT diodes and Gunn devices at frequencies above 100 GHz and gives an overview of design procedures and fabrication technologies. The experimental results on D-band InP Gunn devices agree well with previously reported simulations [3] and indicate that fundamental mode operation can be extended to the upper D-band. Since IMPATT diodes, TUNNETT diodes and Gunn devices are nonlinear devices, this paper also focuses on harmonic power extraction. Preliminary results show that even in a non-optimized circuit power levels up to 0.39 mW around 220 GHz can be extracted.

2. Device Design

The design of the GaAs D-band single-drift flat-profile IMPATT diodes was based on an extended small-signal model for the avalanche region and a large-signal approximation for the drift region and followed the same procedure as previously used in the design of GaAs W-band diodes [4]. The design of the W-band TUNNETT diodes was based on a simplified large-signal model [5] and GaAs material parameters derived from measurements on heavily doped $p^{++}n^{+}$ junctions and GaAs IMPATT diodes [6]. Figures 1 and 2 show the nominal doping profiles of the D-band IMPATT diode and W-band TUNNETT diode, respectively.

An Ensemble Monte Carlo program has been developed to simulate Gunn devices. Since a Monte Carlo method requires accurate values for a large number of material parameters, first InP W-band Gunn devices with $n^{+}n^{-}n^{+}$ structures similar to published designs were fabricated and tested. The appropriate material parameters were selected by comparing dc and high-frequency measurements with results predicted by the model [3]. During this selection process two different structures for operation at D-band frequencies were designed, one with a flat doping profile and one with a graded doping profile [7]. Figures 3 and 4 give the nominal doping profiles of the two Gunn devices.

3. Fabrication Technology

A lattice matched $Al_{0.55}Ga_{0.45}As$ layer grown between the device layer of Figures 1 or 2 and the GaAs substrate or a lattice matched $In_{0.53}Ga_{0.47}As$ layer grown between the device layers of Figure 3 or 4 and the InP substrate allows the use of a selective etching technology [3,8]. This technology gives substrateless devices on a 15 to 20 µm thick integral heat sink. Figure 5 outlines the main steps in this fabrication technology. Before the epitaxial side of the MBE-, CBE- or MOCVD-grown wafer is metallized with Ti/Pt/Au for a p^+ ohmic contact (TUNNETT diode) or Ni/Ge/Au/Ti/Au for an n^+ ohmic contact (Gunn device), grooves are selectively etched down to the etch-stop layer (AlGaAs or InGaAs) to divide the device layers into square shaped islands. This reduces the stress in the device layers during annealing. In addition, the trenches shape the evaporated metal layers and plated gold layer of the integral heat sink thus increasing the mechanical strength of the metal layers for the subsequent processing steps after the substrate and the etch-stop layer have been removed in selective etches. The top n^+ ohmic contact (Ni/Ge/Au/Ti/Au) is defined by standard lift-off technology. After an additional metallization (Ti/Au/Ti) step a second photolithography process produces a hole on top of each n^+ ohmic contact. The top Ti layer is removed and up to 3 µm of gold can be electroplated through these holes in order to ease bonding. The remaining Ti/Au/Ti layers between the contacts are removed in wet etches. Mesas are formed using a standard wet etch and the ohmic contacts are annealed on a hot plate. The heat sink is diced to give individual devices. TUNNETT diodes with nominal diameters of 25-35 µm or Gunn devices with nominal diameters of 35-45 µm are mounted on gold plated copper blocks.

The high operating current densities around 60 $kAcm^{-2}$ and corresponding high power densities in D-band IMPATT diodes require operation on diamond heat sinks. Therefore another, previously reported, selective etching technology [9] was employed in the fabrication of the IMPATT diodes. The diodes are thermocompression bonded on to metallized diamond heat sinks.

To minimize parasitic elements of the package and to find the optimum impedance transformation an open package with four stand-offs and tapered ribbons was chosen for all the IMPATT and TUNNETT diodes and for most of the Gunn devices. Some of the Gunn devices were packaged with metallized quartz rings and tapered gold ribbons.

4. Experimental results

A full-height waveguide cavity (WR-10 for W-band, WR-6 for D-band) with a resonant cap on top of the device and with a back short at one flange has been successfully used for all the two-terminal devices reported in this paper. The gold plated copper block of the heat sink forms the bottom of the waveguide. In some cases the RF output power could be slightly increased by using an E-H-tuner at the output flange of the cavity.

In Figure 6 the RF output power, the dc to RF conversion efficiency and oscillation frequency of one D-band IMPATT diode are plotted as a function of the dc bias. For the maximum applied bias current an output power of 15 mW was obtained. The corresponding efficiency was 1.5 % at the oscillation frequency of 135.3 GHz. The highest oscillation frequency of another IMPATT diode was 137.3 GHz with an output power of 4 mW [10]. Figure 7 compares the performance of D-band IMPATTT diodes fabricated from two wafers with an active layer of a nominal width between 0.285 µm and 0.28 µm and of a nominal doping concentration between 2.7×10^{17} cm^{-3} and 2.8×10^{17} cm^{-3}. Diodes made from wafer (b) exhibit slightly higher power levels and efficiencies at frequencies above 120 GHz. Figure 8 shows the measured spectrum of a free running D-band IMPATT diode oscillator with 5 mW at 120.7 GHz and proves that the oscillations have a clean spectrum.

A plot of the RF output power and dc to RF conversion efficiency versus oscillation frequency in Figure 9 summarizes the experimental results for the eleven best devices of the W-band TUNNETT diodes that have been mounted and tested to date. The peak in output power (35 mW) and efficiency (3.5 %) at 103 GHz occurs close to the design frequency of 100 GHz and confirms that the first order design rules [5] accurately predict the operating frequency of the TUNNETT diodes. It also indicates that the average, high field, high temperature electron drift velocity in GaAs TUNNETT diodes is close to 4.6×10^6 cms^{-1} [8]. These findings have been verified by more detailed large-signal device simulation programs [11].

Figure 10 compares the experimental results obtained from the InP Gunn devices with the flat doping profile (grown by CBE) and with the graded doping profile (grown by MOCVD) between about 90 GHz and 165 GHz. The best device with the flat doping profile yielded an RF output power of 33 mW with a corresponding dc to RF conversion efficiency of 1.75 % at 108.3 GHz. To the authors' knowledge, these are the highest reported values for an $n^+n^-n^+$ structure. The decrease in performance at higher frequencies seems to be rather pronounced and may be explained by non-optimized ohmic contacts. As expected from the simulations, devices with the graded doping profile exhibit the better performance. RF output power levels of 21 mW at 120.6 GHz, 17.5 mW at 133.7 GHz and 8.4 mW at 155.4 GHz were obtained from the so far best devices. The corresponding dc to RF conversion efficiencies were 1.25 %, 1 % and 0.6 %, respectively. Oscillations up to about 165 GHz (< 1 mW) have also been detected in a reduced-height WR-4 waveguide cavity with a coaxial post.

As can be seen in Figure 11a for 14 mW at 121 GHz and in Figure 11b for 3.6 mW at 156 GHz the spectra of the free running Gunn device oscillators are clean up to the highest oscillation frequencies. Using a self-injection locking method a loaded Q value of 54 was measured at 156 GHz. This low a value indicates that the Gunn device operates in the fundamental-frequency mode. Typical loaded Q values between 30 and 105 were determined for various Gunn devices with the two doping profiles at other D-band frequencies and corroborate this conclusion.

5. Second harmonic power extraction

IMPATT diodes, TUNNETT diodes and Gunn devices are nonlinear devices and are expected to have higher harmonics in their output signal. Therefore, a 1"-long WR-3 waveguide section with a cut-off frequency of 173.28 GHz was inserted between the 1"-long WR-6 waveguide of a D-band thermistor power head (calibrated around 160 GHz) and the flange of the full height WR-10 waveguide cavity for the W-band devices or the full-height WR-6 waveguide cavity for the D-band devices. Estimated 3 dB attenuation were taken into account for the losses in the 3"-long waveguide and for the mismatch in the power head, although the correction factor for the D-band thermistor might be considerably higher at around 220 GHz.

The back short of the cavity was adjusted for maximum output power. No other additional tuning elements at the fundamental frequency, nor at the second-harmonic frequency were used in the cavity at this point.

A W-band IMPATT diode with a maximum RF output power of 140 mW and a dc to RF conversion efficiency of 4.2 % at 93.4 GHz yielded an output power of 0.12 mW at a second harmonic frequency of about 182 GHz and a bias current of about $^2/_3$ the maximum bias current. A D-band IMPATT diode with 20 mW at 120 GHz had an output power of 13 µW at the second harmonic of 240 GHz. An explanation of low up-conversion efficiency can be found in the decrease of the derivative of the ionisation rates with respect to the electric field strength at electric fields above 500 $kVcm^{-1}$ [4,12]. This decrease causes the avalanche process to become more and more linear [12] and the higher harmonics to disappear in the output signal of the diode.

Three different D-band Gunn devices yielded RF output power levels of 0.39 mW at 220 GHz with a fundamental to second-harmonic power conversion efficiency of 2.5 %, 0.09 mW at 228 GHz and 0.12 mW at 232 GHz. The power levels are similar to the values obtained with a more optimized second-harmonic oscillator circuit [13]. A W-band InP Gunn device tested in a full-height WR-10 waveguide gave 3.5 mW at 156.3 GHz with a fundamental to second-harmonic power conversion efficiency of 10 %. The second harmonic output of this W-band oscillator was measured in a WR-6 waveguide test setup.

Three different TUNNETT diodes had RF power levels of 41 µW at 200 GHz, 0.25 mW at 223.5 GHz and 0.12 mW at 225 GHz. The RF output power level of the TUNNETT diode with the 0.25 mW at the second harmonic was 14 mW at 112.5 GHz. Thus a conversion efficiency of 1.8 % between fundamental and second-harmonic output power can be calculated. This value is very similar to the unpublished result of a V-band TUNNETT diode which had a conversion efficiency of 2 % and an output power of 0.5 mW at the second-harmonic frequency of 121 GHz. The V-band diode was tested in a full-height WR-15 waveguide cavity and the second-harmonic output was measured in a WR-6 test setup. To measure the spectrum of the W-band TUNNETT diode at the second harmonic, the D-band thermistor power head was removed and the WR-3 waveguide of a harmonic mixer (175-325 GHz) was connected to the 1"-long WR-3 waveguide piece. Figure 12 shows the spectrum of the TUNNETT diode at an RF output power of 0.2 mW and proves that the oscillations have a clean spectrum even at the second harmonic of 223.5 GHz. This is the highest reported frequency for CW operation of TUNNETT diodes.

6. Conclusion

The experimental results from the D-band IMPATT diodes are the best reported to date. The power levels and efficiencies of the W-band TUNNETT diodes above 93.5 GHz are the highest reported so far and compare favorably to the values of Gunn devices [15-17] above 100 GHz. InP Gunn devices can be operated in fundamental mode up to D-band frequencies exceeding the power levels that have been published so far. These experimental results confirm recent theoretical findings. Free running oscillators with all these two-terminal devices exhibit clean spectra which makes them excellent candidates for local oscillator applications.

Second harmonic power extraction has been successfully demonstrated with IMPATT diodes, TUNNETT diodes and Gunn devices. Useful power levels with clean spectra were extracted from TUNNETT diodes and Gunn devices. Higher power levels and harmonic power extraction at higher frequencies can be expected with more optimized circuits.

Acknowledgments

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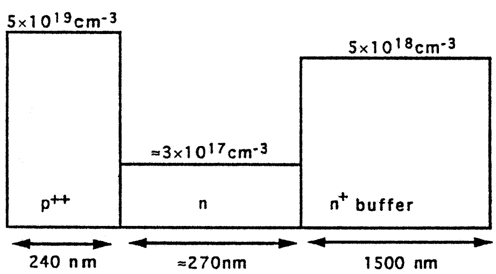


Fig. 1: Nominal device structure of a GaAs D-band single-drift flat-profile IMPATT diode.

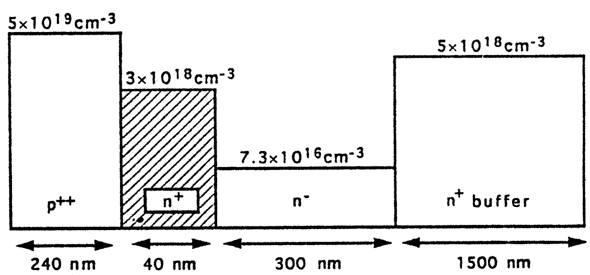


Fig. 2: Nominal device structure of a GaAs W-band single-drift TUNNETT diode.

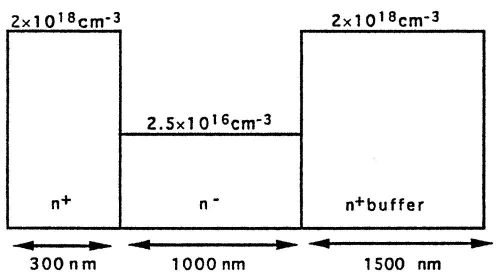


Fig. 3: Nominal device structure of an InP D-band flat-profile Gunn device.

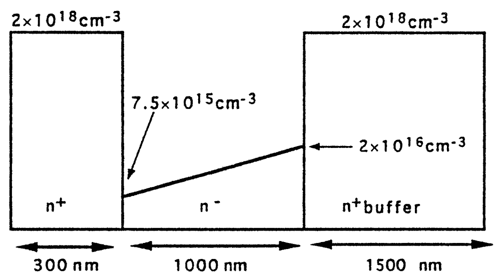


Fig. 4: Nominal device structure of an InP D-band graded-profile Gunn device.

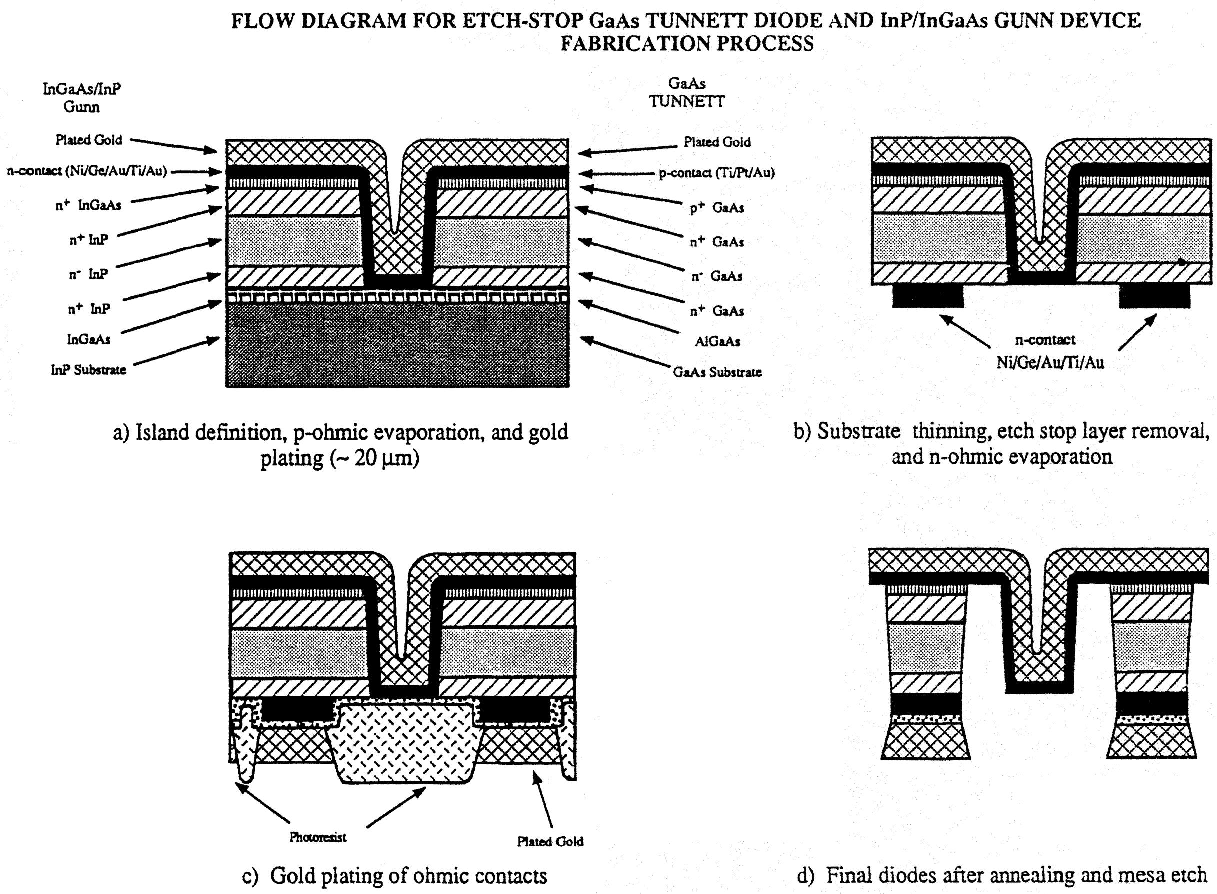


Fig. 5: Flow chart for mesa-type two-terminal device fabrication.

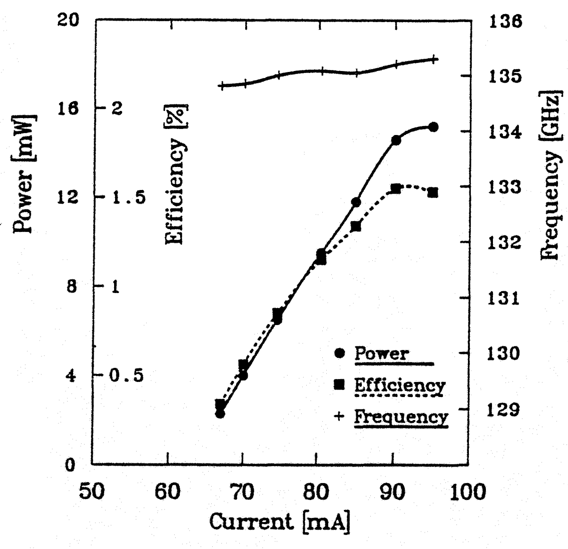


Fig. 6: Output power, efficiency and oscillation frequency as a function of bias current for a GaAs D-band single-drift flat-profile IMPATT diode.

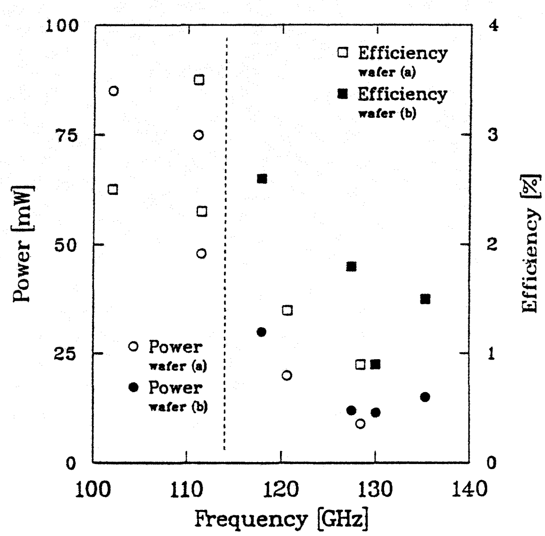


Fig. 7: Output power and efficiency versus oscillation frequency for different GaAs D-band single-drift flat-profile IMPATT diodes.

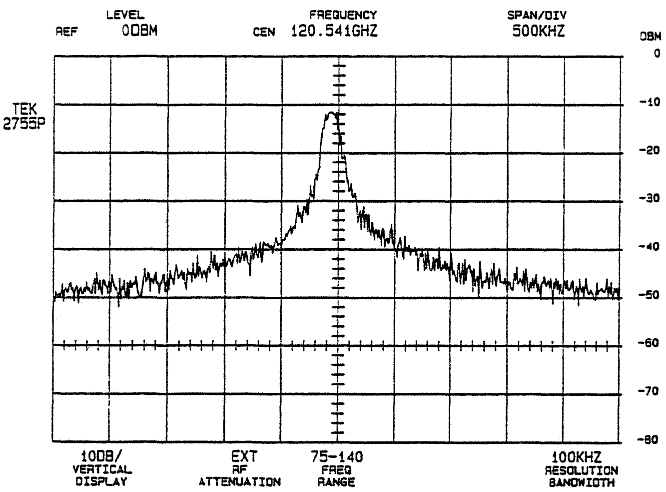


Fig. 8: Spectrum of an GaAs D-band IMPATT diode free running oscillator, power level 5.2 mW, center frequency 120.541 GHz, vertical scale 10 dB/div, horizontal scale 500 kHz/div, BW 100 kHz.

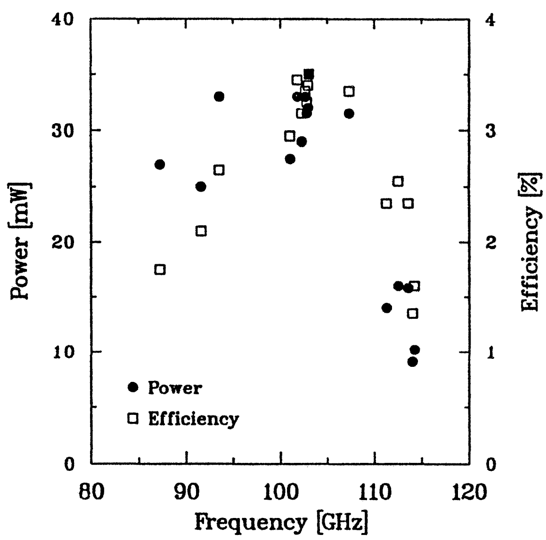


Fig. 9: Output power and efficiency versus oscillation frequency for different GaAs W-band single-drift TUNNETT diodes.

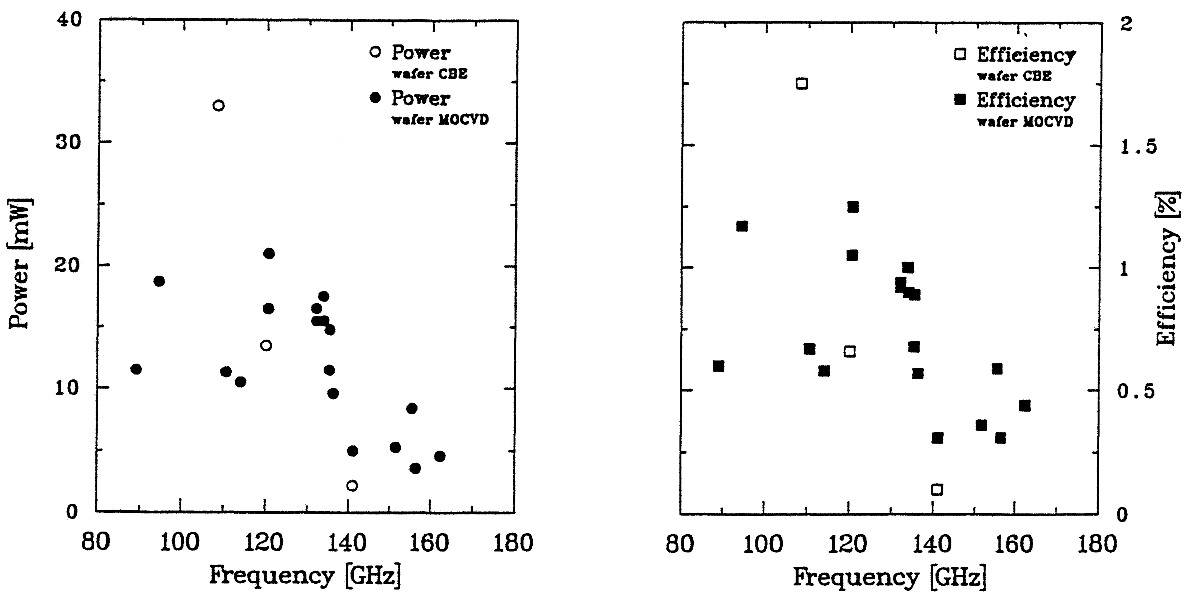
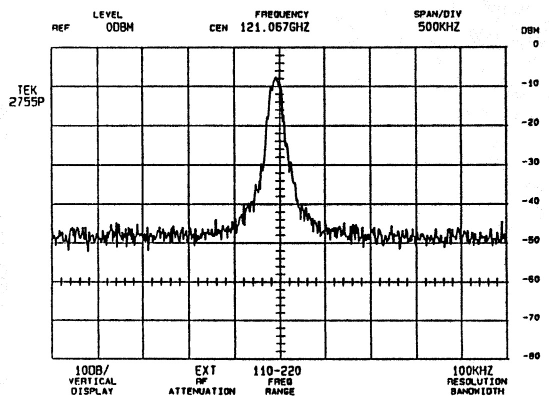
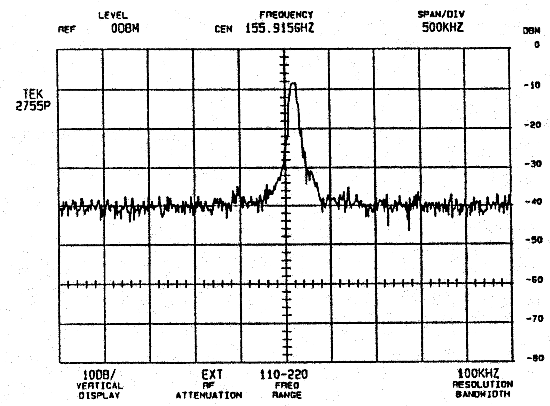


Fig. 10: Output power and efficiency versus oscillation frequency for different InP D-band Gunn devices in W-band and D-band.



(a)

Fig. 11: Spectrum of an InP D-band Gunn device free running oscillator, power level 14 mW, center frequency 121.067 GHz, vertical scale 10 dB/div, horizontal scale 500 kHz/div, BW 100 kHz.



(b)

Fig. 11: Spectrum of an InP D-band Gunn device free running oscillator, power level 3.6 mW, center frequency 155.915 GHz, vertical scale 10 dB/div, horizontal scale 500 kHz/div, BW 100 kHz.

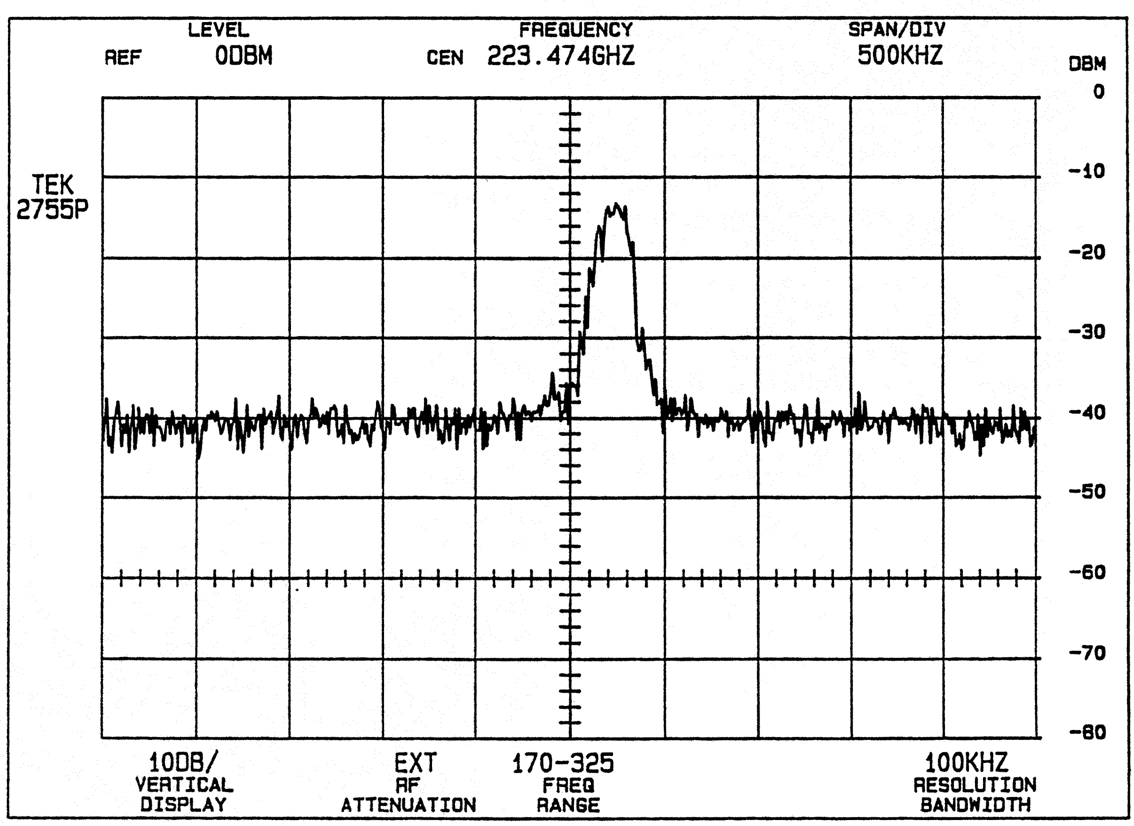


Fig. 12: Spectrum of a W-band TUNNETT diode free running oscillator in second harmonic mode, power level 0.2 mW, center frequency 223.474 GHz, vertical scale 10 dB/div, horizontal scale 500 kHz/div, BW 100 kHz.