# Efficient Power Combining with D-Band (110–170 GHz) InP Gunn Devices in Fundamental-Mode Operation

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***Abstract*— D-band InP Gunn devices on diamond heat sinks with an $n^+n^-n^+$ structure and a graded doping profile in the active region were tested as free-running oscillators in individual resonant-cap full-height waveguide cavities. Subsequently, matched oscillators were power-combined in an in-line dual-cavity configuration. Combined radio frequency (RF) power levels of more than 300 mW at 106 GHz, 130 mW at 136 GHz, and more than 100 mW at 152 GHz were achieved. These RF power levels are the highest reported to date from either single or power-combined Gunn devices at W-band and D-band frequencies. They correspond to combining efficiencies of more than 80%, 86%, and more than 100% as well as overall dc-to-RF conversion efficiencies of 1.95%, 1.25%, and 0.90%, respectively. Similar to oscillators with single devices, these power-combined Gunn device oscillators exhibit good tunability and a phase noise of well below −100 dBc/Hz, measured at a frequency off the carrier of 500 kHz.**

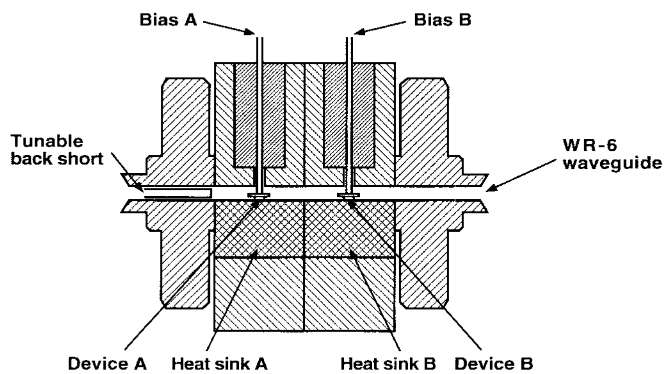


Fig. 1. Schematic of the in-line dual-cavity waveguide circuit for Gunn device power combining.

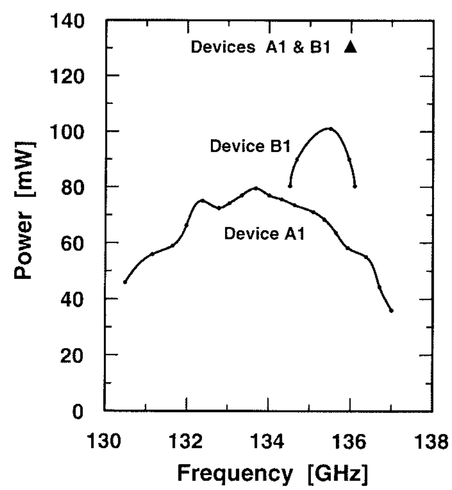


Fig. 2. Mechanical tuning characteristics of devices $A$ and $B$ of pair #1 in individual oscillators at 80% and 100% of the maximum dc bias, respectively.

## I. Introduction

HIGH-RESOLUTION radars as well as frequency multipliers in receiver arrays for radio astronomy and spectroscopic studies of the atmosphere demand increasingly higher radio frequency (RF) power levels from low-noise oscillators above 100 GHz. InP Gunn devices on diamond heat sinks for operation in the fundamental-mode [1] yielded RF power levels of more than 130 mW around 132 GHz as well as more than 60 mW around 151 GHz and are capable of meeting these requirements as local oscillators (LO) in receiver systems. Additionally, long-term stability of crucial RF performance characteristics is being demonstrated in a still-ongoing experiment that was initiated in mid-April 1996 [2]. However, a significant decline in RF power levels was observed with all measured devices at oscillation frequencies above 150 GHz. Although these power levels still suffice to drive a frequency multiplier or may even, e.g., around 130 GHz, exceed the power-handling capabilities of present multipliers, waveguide components like isolators and directional couplers between the LO and the multiplier stage may reduce the RF power that is available in an actual receiver circuit. These waveguide components are often necessary to form a phase-locked loop (PLL) for frequency control. Increase in available RF power, above 150 GHz in particular, is expected from three approaches, which include an active region optimized for operation at 150–170 GHz, second-harmonic power extraction from devices on diamond heat sinks, and power combining. The latter will be discussed in this letter.

## II. Experimental Setup

Power combining in an in-line configuration of between two and four waveguide cavities was demonstrated with Gunn devices and TUNNETT diodes up to W-band (75–110 GHz) frequencies [3]–[5], and combining efficiencies exceeding 80% were easily achieved. Therefore, a quite similar approach was adopted at D-band (110–170 GHz) frequencies. Four devices, which had been tested previously as single devices in individual WR-6 waveguide cavities [1], were selected for

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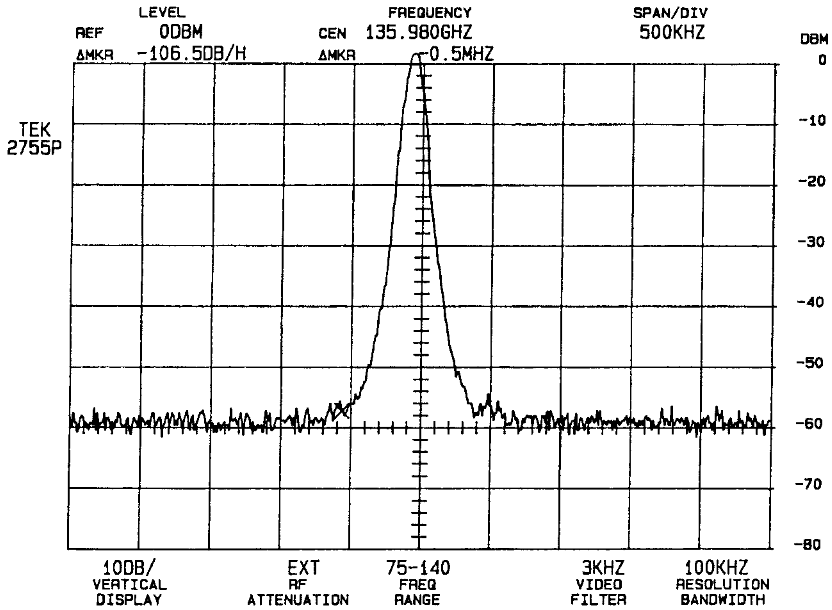



Fig. 3. Spectrum of the oscillator with device pair #1 of Table I. Power level: 130 mW, center frequency: 135.980 GHz, vertical scale: 10 dB/div, horizontal scale: 500 kHz/div, BW: 100 kHz, VBW: 3 kHz.

TABLE I
RESULTS OF DUAL-CAVITY POWER COMBINING WITH InP GUNN DEVICES

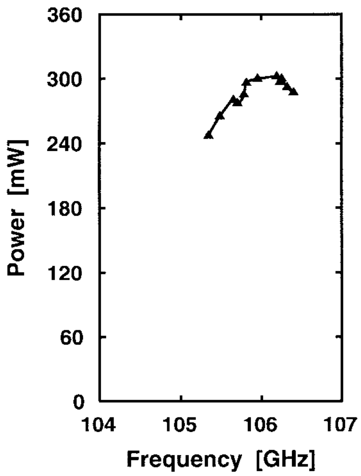
| Device Pair # | Frequency | Power A & B | Overall Efficiency | Power A | Power B | Combining Efficiency | Frequency A | Frequency B |
|---|---|---|---|---|---|---|---|---|
| | [GHz] | [mW] | [%] | [mW] | [mW] | [%] | [GHz] | [GHz] |
| 1 | 135.98 | 130 | 1.25 | see Figure 2 | 101 | 86 | see Figure 2 | 135.50 |
| 2 | 151.76 | 105 | 0.90 | 41 | 62 | 102 | 150.93 | 151.03 |
| 3 | 106.17 | 305 | 1.95 | 204 | 166 | see Text | 102.73 | 103.63 |

optimum RF performance at similar frequencies and grouped in two pairs. Two cavities were then mounted back to back with a tunable back short at one side, and the Gunn devices were biased from two separate dc power supplies as illustrated in Fig. 1. Similar to the measurements of individual devices in their respective cavities, no E-H tuner or other additional tuning elements were part of the test setup. The typical spacing between the devices was determined mainly by the mechanical dimensions of the cavities and varied from about 8.1 mm to 8.4 mm. The direct reading frequency meter in the measurement setup was used to scan for any additional signals in the full waveguide band. The frequency range of at least $\pm$500 MHz around the oscillation frequency was checked for spurious signals and signs of bias oscillations with a spectrum analyzer and a harmonic mixer.

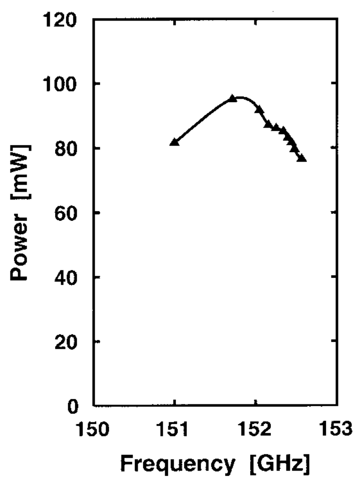
## III. RESULTS

The best results from the individual devices as well as the results in the power-combining circuit are given in Table I. The devices of pair #1 were not a close match as the optimum frequencies at maximum dc bias differed by more than 3 GHz. The spacing of the devices in this power-combining circuit favored oscillations around 136 GHz, but a second device with an oscillation frequency closer to 136 GHz was not available at this point. Therefore, only device $B$ in pair #1 was biased at the maximum dc input power, whereas the bias of device $A$ was reduced to 80% of the maximum dc input power in order to widen the tuning range and provide enough RF power from device $A$ near 136 GHz. The tuning characteristics in Fig. 2 show the actual RF power levels that were available from each device at the chosen bias conditions and the oscillation frequency of the combined devices. The combined RF output power of 130 mW with a corresponding overall dc-to-RF conversion efficiency of 1.25% is also included as a reference point in Fig. 2. The combining efficiency of 86% at 135.98 GHz is attributed to the difference in the optimum oscillation frequencies. For the second pair of power-combined devices, the optimum oscillation frequencies at maximum RF output power were much closer and, therefore, this experiment resulted in a much higher combining efficiency of $>$100%. The combined RF output power reached 105 mW with a corresponding overall dc-to-RF conversion efficiency of 0.90%.

Although the device structure was not optimized for operation at W-band frequencies, state-of-the-art performance with an RF power of 185 mW at 101.98 GHz was achieved with




(a)




(b)

Fig. 4. Mechanical tuning characteristics of the power-combined device pairs (a) #3 and (b) #2 of Table I.

one device [1]. A device, which had not yet been tested in a WR-10 waveguide cavity, yielded more than 200 mW with a corresponding dc-to-RF conversion efficiency of 2.6% at an oscillation frequency of 102.73 GHz. When two WR-10 waveguide cavities were used instead in the configuration of Fig. 1, this device was combined in pair #3 with a device that yielded 166 mW at 103.63 GHz. The combined RF output power exceeded 300 mW at an oscillation frequency of 106.17 GHz, which corresponds to an overall dc-to-RF conversion efficiency of 1.95%. In the single-cavity experiment with either device, only less than 50% of the RF power at the optimum oscillation frequency was generated around 106 GHz. Therefore, the combining efficiency is referred to the maximum total RF power of the two devices around 103 GHz. Nonetheless, it is more than 80%.

The devices of the three pairs in each experiment readily appeared to be phase locked as the bias was increased and the back short was tuned for maximum output power. No additional signals in the respective full waveguide band or signs of bias oscillations were detected, neither with the spectrum analyzer nor with the D-band direct reading frequency meter in case of device pairs #1 and #2 nor the W-band direct reading frequency meter in case of device pair #3. In the three experiments, the two devices of a pair were biased from separate dc power supplies, but bias voltages of the devices in pairs #2 and #3 at maximum combined RF power are within $\pm 2\%$ of each other. No change in the maximum combined RF power was observed when the devices of pair #2 as well as pair #3 were biased from one common dc power supply. The power-combined Gunn devices kept the same clean spectra and excellent noise properties as already demonstrated with single devices in free-running oscillators at D-band frequencies [1]. As illustrated with the spectrum of device pair #1 in Fig. 3, the phase noise at a frequency of 500 kHz off the carrier remained below $-106$ dBc/Hz. Since this phase noise reached the noise floor of the employed spectrum analyzer with a harmonic mixer, the corrected phase noise at maximum RF output power was estimated to be well below $-109$ dBc/Hz at 500 kHz off the carrier. An uncorrected phase noise of below $-100$ dBc/Hz and below $-107$ dBc/Hz was recorded with the spectrum analyzer for device pair #2 and #3, respectively. These power-combined devices also retained some of the smooth tuning characteristics that single devices, e.g., device $A$ in pair #1 of Table I, exhibited in free-running oscillators [1]. As can be seen from Fig. 4(a) for device pair #3 and from Fig. 4(b) for device pair #2, RF power levels stayed above 240 and 80 mW, respectively, over a tuning bandwidth of more than 1 GHz. The two devices in either pair #2 or #3 remained phase-locked, and the oscillation frequency changed without jumps as the position of the back short was adjusted.

## IV. Conclusion

Efficient power combining of D-band InP Gunn devices was demonstrated for the first time. Fundamental-mode operation of the Gunn devices permits use of a straightforward in-line dual-cavity configuration. Excellent phase-noise properties, smooth tunability and combining efficiencies in the range of 80% to $>$100% characterize the power-combined D-band Gunn devices. To the authors' knowledge, all RF power levels are the highest reported to date for either single or power-combined devices at W-band and D-band frequencies. The actual spacings of the Gunn devices in the employed power-combining circuits were difficult to verify with fully assembled units. Nonetheless, they appeared to be close to $5/2\lambda_g$, $11/4\lambda_g$, and $13/4\lambda_g$ ($\lambda_g$: guide wavelength) at 106, 136, and 152 GHz, respectively.

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