Performance Improvements in Low-Noise Oscillators and Power Combiners with Harmonic-Mode InP Gunn Devices

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***Abstract*—InP Gunn devices with graded doping profiles were evaluated for second-harmonic power extraction above 260 GHz and third-harmonic power extraction above 400 GHz. The best devices generated radio frequency (RF) output power levels of more than 3.5 mW at 275–300 GHz, 1.6 mW at 329 GHz, and 0.7 mW at 333 GHz. The highest observed second-harmonic frequency was 345 GHz. Two devices each in an in-line power combining circuit generated 6.1 mW at 285 GHz and 2.7 mW at 316 GHz with combining efficiencies of more than 65%. In a third-harmonic mode, the best devices generated 45 μW at 409 GHz, 40 μW at 412 GHz, and 40 μW at 422 GHz.**

I. Introduction

ADVANCES in the performance of compact low-noise fundamental sources at terahertz frequencies are expected to have a far-reaching impact on many applications, such as wideband wireless communications, imaging, and chemical or biological sensing [1]. Transferred-electron devices, long known as Gunn devices and widely utilized as low-noise sources up to millimeter-wave frequencies, were originally thought to be limited to frequencies below 200 GHz [2]. Accurate device design tools [3], advanced fabrication technologies, and appropriate thermal management [4] vastly improved the performance of millimeter-wave InP Gunn devices and extended their operation in a second-harmonic mode to *J*-band (220–325 GHz) frequencies [5]–[7]. Power combining of oscillators is the method of choice to provide systems applications with higher radio frequency (RF) power levels and different techniques are widely known for oscillators at millimeter-wave frequencies [8]. The technique of a resonant-cavity combiner was demonstrated with Si impact avalanche transit-time (IMPATT) diodes up to 217 GHz [9] and this had so far been the highest frequency where a combined continuous-wave (CW) RF output power of more than 1 mW had been reported. This paper describes the performance improvements in second- and third-harmonic InP Gunn devices and the first successful demonstration of power combining above 260 GHz.

II. Device Performance in a Second-Harmonic Mode

Devices with two similar graded doping profiles as shown in Fig. 1 were evaluated. These profiles were designed for efficient operation in a second-harmonic mode at 240 GHz and above [7]. Devices with diameters of 25–40 μm were selected and mounted on diamond heat sinks. Except for some different equipment and minor configuration changes [10], [11], the same test setup and the same type of a full-height WR-6 waveguide cavity [5], [6] was used.

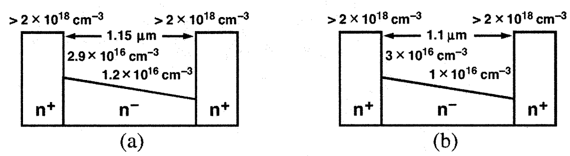

Fig. 1. (a) and (b) Nominal doping profiles of InP Gunn devices evaluated for second-harmonic power extraction.

Fig. 2 summarizes only the highest RF output power levels of the tested devices. Examples are the RF output power (and corresponding dc-to-RF conversion efficiency) of 4.8 mW (0.31%) at 281.9 GHz, 3.7 mW (0.32%) at 297.1 GHz, 1.6 mW (0.19%) at 329.1 GHz, and 0.7 mW (0.07%) at 332.8 GHz from devices with the doping profile of Fig. 1(b). Devices with the doping profile of Fig. 1(a) tended to work better at frequencies lower than those of devices with the profile of Fig. 1(b) and the best performance was an RF output power of 3.9 mW at 274.75 GHz with a corresponding dc-to-RF conversion efficiency of 0.24%. Conversely, the highest second-harmonic frequency of 344.85 GHz was observed with a device of the profile of Fig. 1(b). An RF output power of more than 0.1 mW was measured and the lack of a signal at 344.85/1.5 GHz confirmed operation in a second-harmonic mode. Operating active-region temperatures of these second-harmonic mode devices on diamond heat sinks were estimated to be typically much below 150 °C, and, therefore, reliable long-term operation is expected from these devices.

Although the differences in the doping profiles of Fig. 2 are small, they are the main cause of the observed performance differences. As described in Section IV, devices from both doping profiles generate state-of-the-art RF output power levels in a third-harmonic mode, which precludes major differences in contact and other series resistances. In addition, differences in performance are also present in the results of device simulations [3] as shown in Fig. 3. Devices with the doping profile of Fig. 1(a) exhibit better performance at lower frequencies and a steeper decline in RF output power levels

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above 260 GHz when compared with devices of the other doping profile.

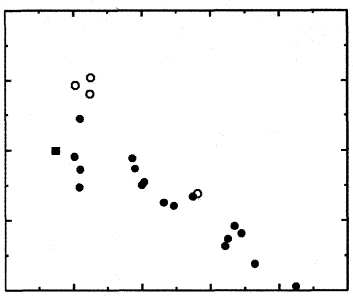

Fig. 2. RF performance of InP Gunn devices on diamond heat sinks, operating in a second-harmonic mode in the frequency range 270–350 GHz. ■: doping profile of Fig. 1(a); ●: doping profile of Fig. 1(b); **O**: power-combined devices with doping profile of Fig. 1(b). Numbers next to the symbols denote dc-to-RF conversion efficiencies in %.

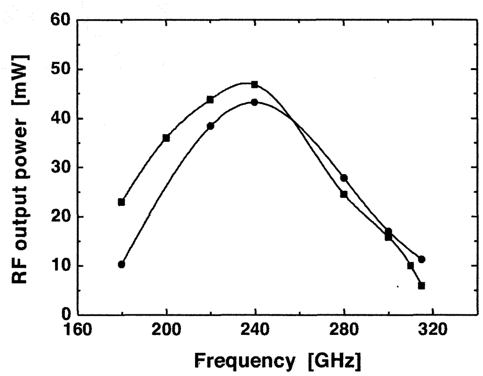

Fig. 3. Comparison of the predicted RF performance of InP Gunn devices operating in a second-harmonic mode in the frequency range 180–320 GHz. ■: doping profile of Fig. 1(a); ●: doping profile of Fig. 1(b).

III. POWER COMBINING

Phase lock between devices generally occurs in a power-combining circuit only if the devices are coupled at the fundamental and second-harmonic frequencies [12]. This is achieved with the in-line power-combining circuit as shown in Fig. 4. Two full-height WR-6 waveguide cavities, as used before for second-harmonic power extraction from individual devices, are mounted back-to-back and four dowel pins in their inner flanges help with the performance-critical alignment. A standard tunable WR-6 waveguide short is connected to the outer flange of one of the cavities. The section of a WR-3 waveguide, connected to the outer flange of the other cavity, keeps the signals at the fundamental frequencies from reaching the power meter.

Two pairs of devices with similar oscillation frequencies as shown in TABLE I were used in these experiments. Power combing and phase-lock conditions were achieved with devices of pair #1 for three bias conditions and three positions of the tunable back short. At the same bias voltages, *i.e.*, those for maximum RF output power from the individual devices, a combined RF output power of 6.1 mW was measured at 285 GHz. This power level corresponds to a combining efficiency of 75% and an overall dc-to-RF conversion efficiency of 0.2%.

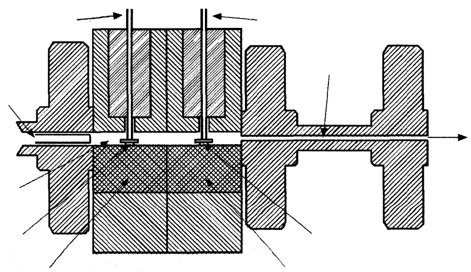

Fig. 4. Schematic of the WR-6 in-line waveguide power-combining circuit with the WR-3 output waveguide.

As can be seen from TABLE I, device B generated more than 3.2 mW at two different positions of the back short and corresponding second-harmonic frequencies. As a result, phase lock in the power combiner also occurred at 280.5 GHz with a combined RF output power of 5.8 mW. Furthermore, phase-lock conditions were achieved at a reduced dc input power (approximately 88%) for device A and close to maximum dc input power for device B (> 95%) and a combined RF output power of 5.6 mW at 284.8 GHz, which corresponds to a combining efficiency of 85%.

TABLE I
RESULTS OF DUAL-CAVITY POWER COMBINING WITH INP GUNN DEVICES IN A SECOND-HARMONIC MODE

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	280.5	5.8	0.19	4.8	3.8	67	281.9	280.3
1	284.8	5.6	0.19	3.4	3.1	85	282.0	285.0
1	285.0	6.1	0.2	4.8	3.2	75	281.9	284.9
2	316.3	2.7	0.12	1.5	1.4	65 (est.)†	325.0	325.0

† estimated value, see text.

The devices of pair #2 exhibited very similar performance at 325 GHz. However, the spacing between the devices in the power combiner as determined by the individual cavities was fixed in all experiments and not as favorable as around 282 GHz. Therefore, phase-lock conditions occurred at a lower frequency of 316.3 GHz with an RF output power of 2.7 mW. As the individual devices are expected to have generated RF power levels approximately 30% higher at 316 GHz than at 325 GHz, the combining efficiency was estimated not to be 93%, but closer to 65%.

To verify that each pair of devices was phase-locked and without bias oscillations, the frequency range of 260–360 GHz was scanned for spurious signals with the spectrum analyzer and harmonic mixer and none were found. Phase lock occurred instantly at always the same frequency as soon as both devices were biased. This was also independent of whether one device was turned on first or both devices were turned on at the same time.

The spectra of the oscillators with power-combined devices were as clean as those with single devices and this corresponds well to the clean spectra of power-combined devices in the fundamental mode at *D*-band [13]. Fig. 5 shows one example for pair #1 at 280.5 GHz.

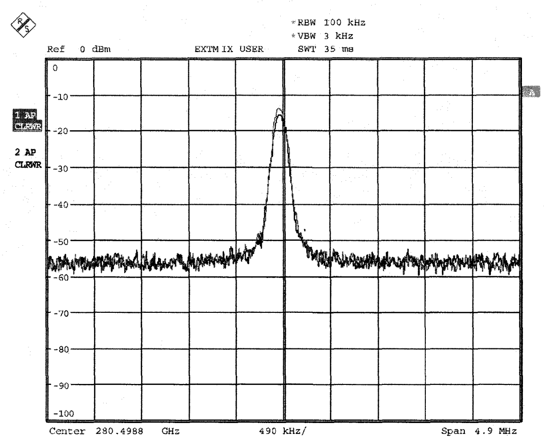

Fig. 5. Spectrum of the oscillator with device pair #1. Power level: 5.8 mW, center frequency: 280.499 GHz, vertical scale: 10 dB/div, horizontal scale: 490 kHz/div, resolution bandwidth: 100 kHz, video bandwidth: 3 kHz, reference level not calibrated.

IV. Third-Harmonic Power Extraction

Devices on diamond heat sinks with the graded doping profiles of Fig. 1 and mesa diameters between 25 μm and 40 μm were also evaluated for third-harmonic power extraction. They were tested in the same type of a full-height WR-6 waveguide cavity as before [4]–[7], [11], [13] and, as shown in Fig. 6, the same tunable short as in Fig. 4 was mounted on one flange of the cavity to allow for frequency and power fine-tuning. A dielectric-filled conical horn was used to emit the third-harmonic power and connected to the other flange through a short waveguide section [14]. The rectangular waveguide section (approximate size WR-2) of the conical horn with a cut-off frequency of more than 285 GHz blocks the signals at the fundamental and second-harmonic frequencies. Further details of the test setup can be found in [14].

The InP Gunn devices with the smallest areas generally showed the best performance and such observations had been reported previously for other two-terminal devices [10], [15]. Careful assembly including the alignment of the waveguide transition proved critical in these experiments and improved the performance considerably from previous results in the frequency range 400–425 GHz [16]. RF power levels of more than 45 μW at $3f_1$ = 409 GHz and 40 μW at $3f_2$ = 412 GHz from device A with the doping profile of Fig. 1 (a), and 40 μW at $3f_3$ = 422 GHz from device B with the doping profile of Fig. 1 (b) are the best results and were measured with a Thomas Keating quasi-optical power meter. The exact oscillation frequencies were determined using the IDENTIFY function of a spectrum analyzer with an external *J*-band harmonic mixer [14]. Fig. 7 shows the clean spectrum of the free-running oscillator with the RF output power of 40 μW. The narrow line width of the signal corresponds well to the clean spectra and excellent noise performance of InP Gunn devices with the same or similar graded doping profiles in the fundamental and second-harmonic modes [6].

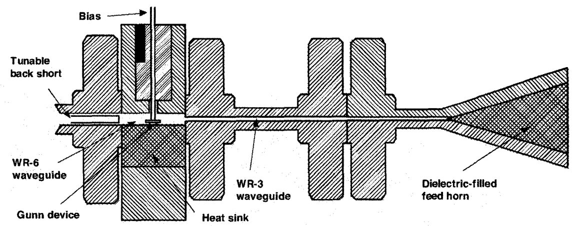

Fig. 6. Schematic of the WR-6 waveguide cavity, WR-3 waveguide section, and conical horn for third-harmonic power extraction.

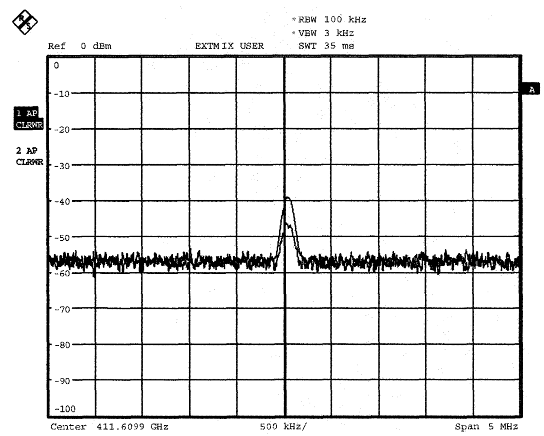

Fig. 7. Spectrum of a free-running InP Gunn device oscillator in a third-harmonic mode. RF power level: 0.04 mW, center frequency: 411.610 GHz, vertical scale: 10 dB/div, horizontal scale: 500 kHz/div, resolution bandwidth: 100 kHz, video bandwidth: 3 kHz, reference level not calibrated.

The corresponding second-harmonic frequencies were close to the cut-off frequency of the waveguide section of the horn. Therefore, the same setup with the spectrum analyzer and harmonic mixer was used not only to confirm single-frequency operation, but also to verify that the signals at the second-harmonic frequencies were sufficiently blocked. No other signals were detected, in particular, not around $2f_1$ = 409/1.5 GHz and $2f_2$ = 412/1.5 GHz from device A. Only a weak signal with less than 2 μW was found from device B at $2f_3$ = 422/1.5 GHz.

The RF output power from device A as a function of the dc input power was measured with the power meter PM3 [17], which had a *J*-band corrugated feed horn and the appropriate waveguide transition attached to it [10], [14]. The power readings from the PM3 as shown in Fig. 8 were not corrected for any losses (correction setting of PM3: 0%) nor was a coupling of clearly less than 100% between the two horns of different apertures taken into account [14]. Therefore, the actual output power levels are much higher and the maximum power of 24 μW in Fig. 8 agrees reasonably well with the aforementioned value from the quasi-optical power meter at 412 GHz.

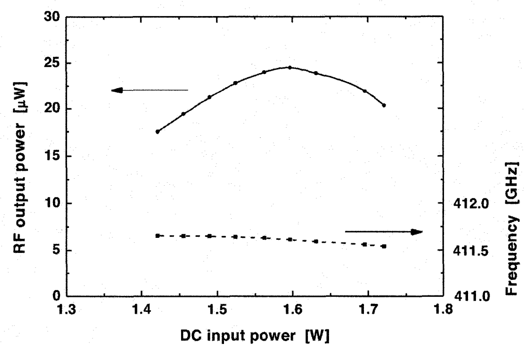

Fig. 8. Uncorrected RF power level readings of an InP Gunn device in a third-harmonic mode at 411.6 GHz as a function of the applied bias. •: RF output power in a third-harmonic mode; ▪: third-harmonic oscillation frequency.

The oscillation frequency in Fig. 8 decreases monotonically with dc input power and the change in RF output power remains well below 2 dB. A tuning range of more than 100 MHz for the Gunn device in a third-harmonic mode is sufficient to stabilize its oscillation frequency in a phase-locked loop.

V. CONCLUSION

All RF output power levels are the highest reported to date from any Gunn device, and more importantly, they are the highest from any fundamental RF source operated at room temperature in the frequency range 290–425 GHz. 344.85 GHz is the highest second-harmonic frequency reported to date for any Gunn device. Typical dc input power levels of less than 1.5 W and bias voltages of less than 6 V allow operation from a battery. Successful power-combining of active two-terminal devices with RF power levels of 2.7 mW and higher was demonstrated for the first time above 220 GHz. Values of DC power consumption and overall dc-to-RF conversion efficiency for individual and power-combined devices in a second-harmonic mode compare favorably with those of RF sources that employ frequency multipliers with GaAs Schottky-barrier or III-V heterojunction-barrier varactor diodes and millimeter-wave driver sources [1], [18]. The measured results confirm the predicted potential of InP Gunn devices as RF sources with substantial amounts of output power up to at least 500 GHz [7]. Improvements in performance of the combiner circuit are expected from more optimized device spacing and an additional tuning element at the second-harmonic frequency. Likewise, improvements in third-harmonic power extraction are expected from more optimized doping profiles and oscillator circuits [14], [16].

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