Fundamental and Subharmonic Excitation for an Oscillator with Several Tunneling Diodes in Series

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***Abstract*—Connecting several tunneling diodes in series shows promise as a method for increasing the output power of these devices as millimeter-wave oscillators. However, due to the negative differential resistance (NDR) region in the dc I–V curve of a single tunneling diode, a circuit using several devices connected in series, and biased simultaneously in the NDR region, is dc unstable. Because of this instability, an oscillator with several tunneling diodes in series has a demanding excitation condition. Excitation using an externally applied RF signal is one approach to solving this problem. This is experimentally demonstrated using an RF source, both with frequency close to as well as with frequency considerably lower than the oscillation frequency. Excitation by an RF source with a frequency as low as one sixth of the oscillation frequency was demonstrated in a proof-of-principle experiment at 2 GHz, for an oscillator with two tunnel diodes connected in series. Strong harmonics of the oscillation signal were generated as a result of the highly nonlinear dc I–V curve of the tunnel diode and a large signal oscillator design. Third harmonic output power comparable to that of the fundamental was observed in one oscillator circuit. If submillimeter wave resonant-tunneling diodes (RTD's) are used instead of tunnel diodes, this harmonic output may be useful for generating signals at frequencies well into the terahertz range.**

I. Introduction

THE RESONANT TUNNELING diode (RTD) is a promising device for generating signals at millimeter wave and terahertz frequencies. It is currently the fastest solid state source, with the highest reported frequency of oscillation at 712 GHz [1]. This frequency may be further increased if a Schottky collector is used instead of the ohmic contact on the top of the device [2]. Because of its highly nonlinear dc I–V curve, which contains a negative differential resistance (NDR) region, an RTD may be used for a variety of applications such as in a self-oscillating mixer [3], frequency multiplier [4], [5] or a low-noise oscillator. Oscillation can be stabilized using quasi-optical techniques to obtain output power with a narrow spectral linewidth [6]. The main disadvantages of RTD oscillators are a small available output power and possible spurious oscillations arising from the low frequency NDR. Series integration of RTD's has been proposed to enhance the output power at millimeter wave frequencies [7], [8]. For example, the available power from ten series integrated RTD's considered in [7] is predicted to be 0.1 W at 100 GHz. A series integrated device may be used as a unit in a power combining grid, to further increase the output power.

Due to the NDR region in the dc I–V curve of a single RTD, a circuit using several RTD's connected in series and biased simultaneously in the NDR region is dc unstable. As a result of this dc instability, there are some special considerations for an oscillator with several RTD's connected in series as compared to a single RTD oscillator. The oscillation amplitude has to be sufficiently large to cover a considerable portion of the positive differential resistance (PDR) region of the dc I–V curve [7], [8]. Besides the high frequency cutoff at which the negative differential resistance (NDR) vanishes, there is also a low frequency cutoff below which oscillation cannot be maintained [9]. The combination of the amplitude cutoff and low frequency cutoff phenomena make the occurrence of low frequency spurious oscillations highly unlikely. A simple dc battery alone cannot be used to bias all RTD's simultaneously in the NDR region of the dc I–V curve. If a dc bias voltage sufficient to bias all RTD's in the middle of the NDR region is applied gradually, the dc instability will divide this voltage so that all the RTD's are biased in the PDR region [8]. There are several ways to solve the biasing problem. One way is to use a fast electrical pulse to bias all diodes simultaneously in the NDR region [7], [8]. Alternatively, an external RF source, with frequency close to the resonant frequency of the circuit, may be used to switch the diode bias points from the PDR to the NDR region, and initiate the oscillation [10], [11]. Subharmonic excitation was also proposed and simulated [12].

In this paper, RF excitation with a frequency close to the oscillating frequency (fundamental frequency excitation) is discussed in more detail than in previous work [11], and the experimental demonstration of subharmonic excitation is presented. Due to the nonlinear multi-frequency nature inherent in the subharmonic excitation scheme, the details of the phenomena involved are quite complicated. A preliminary theoretical explanation is given in [12]. A more detailed theoretical explanation will be given later. Here, we will mainly present a phenomenological description of the experimental findings. A successful excitation was observed in many cases. Excitation with an RF source with frequency below one sixth of the oscillation frequency was demonstrated for a 2-GHz oscillator with two tunnel diodes connected in series. Strong harmonics were generated in the circuit which oscillated with a very large amplitude, due to the high nonlinearity of the tunnel diode dc I–V curve. A third harmonic signal with power comparable to that of the fundamental was observed in this circuit. If series integrated high frequency RTD's are

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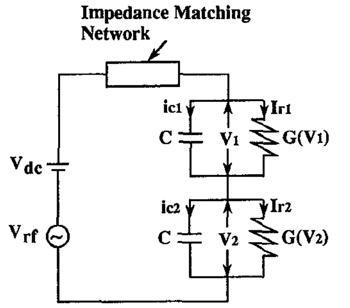

Fig. 1. Equivalent circuit of an oscillator with two tunnel diodes in series.

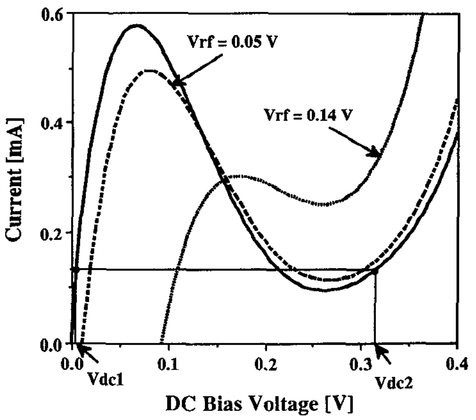

Fig. 2. DC I–V curve and rectified I–V curves for $V_{rf} = 0.05$ V and $V_{rf} = 0.14$ V for a single tunnel diode.

used instead of series connected tunnel diodes, and the third harmonic is extracted, a signal with frequencies well into the terahertz range may be obtained.

The original goal of this work is to build a millimeter-wave oscillator with several RTD's integrated in series. However, since planar RTD's are not readily available, low power tunnel diodes connected in series were used for a proof-of principle experiment at 2 GHz. Tunnel diodes are very similar to RTD's, and are commercially available in a planar package. The performance of an oscillator with several RTD's connected or integrated in series is expected to be similar to the performance of an oscillator with several tunnel diodes connected in series.

II. Theoretical Considerations

A qualitative explanation of the RF instability of a dc stable condition, valid for both fundamental and subharmonic excitation will be presented here. A simple circuit model for an oscillator with two tunnel diodes connected in series is shown in Fig. 1. Each diode is represented as a parallel connection of a nonlinear conductance and a capacitance. Capacitances are assumed to be equal and independent of voltage. All parasitics including series resistance are included in the impedance matching block. If a dc bias voltage sufficient to bias both diodes in the middle of the NDR region is applied gradually, the dc instability will divide this voltage so that one diode is biased on the first rising branch of the dc I–V curve ($V_{\rm dc1}$ in Fig. 2), while the other diode is biased on the second rising branch ($V_{\rm dc2}$ in Fig. 2). The same constant resistive current flows through both diodes and there is no current through the capacitors. The total voltage drop across both diodes is assumed to be equal to the applied dc voltage (the voltage drop across the series resistance is neglected). Hence, before an RF signal is applied

$$I_{r1} = I_{r2}, \tag{1a}$$
$$i_{c1} = i_{c2} = 0, \tag{1b}$$
$$V_{\rm dc1} \neq V_{\rm dc2}, \tag{1c}$$
$$V_{\rm dc1} + V_{\rm dc2} = V_{dc}. \tag{1d}$$

When an RF signal is applied, the dc components of the resistive currents will change, due to the high nonlinearity of the dc I–V curve of the tunnel diode. Assuming the change is slow within one RF period, the changing dc component of the current and the voltage may be defined as the average value over one RF period. Rectified I–V curves, calculated using the procedure described in [13], are shown in Fig. 2 for RF voltage amplitude of 0.05 and 0.14 V. This explanation is only qualitative because we have not taken into account the detailed RF amplitude for each diode. For the diode biased on the first rising branch the dc component of resistive current I_{r1} will decrease, whereas for the diode biased on the second rising branch the dc component of resistive current I_{r2} will increase. Since the total dc and RF current through both diodes has to be constant at any instant in time, in addition to RF capacitive currents there will exist transient capacitive currents i_{c1} and i_{c2} that have to compensate for this change of the averaged resistive currents

$$I_{r1} + i_{c1} = I_{r2} + i_{c2} \tag{2}$$

where the quantities in (2) are the dc components defined over one RF period. If the RF voltage drop on both diodes is assumed to be small, so that it does not affect the dc voltage drop, the transient capacitive currents are then

$$i_{c1} = C\frac{dV_{\rm dc1}}{dt}, \tag{3a}$$
$$i_{c2} = C\frac{dV_{\rm dc2}}{dt}. \tag{3b}$$

During the transient process, capacitive currents have to be of opposite sign, because voltages $V_{\rm dc1}$ and $V_{\rm dc2}$ cannot simultaneously increase or decrease, while the total dc voltage remains constant. Therefore i_{c1} will be positive as shown in Fig. 2 and $V_{\rm dc1}$ will increase, whereas i_{c2} will be negative and $V_{\rm dc2}$ will decrease. Once the dc components of the resistive currents through both diodes are equal, the diodes' bias points are switched from the PDR to the NDR region and the dc bias voltage is equally divided.

A very small RF excitation signal may be used for switching, because even a small RF amplitude produces a large current decrease at bias points on the first rising branch of the dc I–V curve. Any frequency in the operational range of the oscillator may be used for switching. However, after the excitation is turned-off, oscillation cannot build-up and be sustained for all excitation frequencies. If the turn-off time of the RF signal is fast, this transition is less critical and there is a better chance that the oscillation will be present. For fundamental excitation, the turn-off time is not critical,

TABLE I
ONE-DIODE OSCILLATOR DESIGN AND PERFORMANCE

	DESIGN				EXPERIMENT		
CIRCUIT	V_{rf} [V]	P [dBm]	$R_d + jX_d$ [Ω]	X_d / R_d	f [GHz]	P [dBm]	Q_{ext}
1D1	0.136	-18.68	-32.2 -j135.1	4.2	2.0205	-19.83	6
1D2	0.140	-18.76	-30.4 -j136.1	4.5	2.0206	-20.00	10
1D3	0.154	-19.50	-22.6 -j139.7	6.2	2.0651	-20.83	22
1D4	0.164	-20.90	-15.6 -j142.1	9.1	2.0681	-22.33	42

TABLE II
TWO-DIODE OSCILLATOR DESIGN AND PERFORMANCE

	DESIGN				EXPERIMENT		
CIRCUIT	V_{rf} [V]	P [dBm]	$R_{2d} + jX_{2d}$ [Ω]	X_{2d} / R_{2d}	f [GHz]	P [dBm]	QR
2D1	0.136	-15.68	-61.3 -j259.4	4.2			
2D2	0.140	-15.76	-57.8 -j261.2	4.5	1.9879	-18.00	2
2D3	0.154	-16.50	-42.9 -j267.9	6.2	1.9316	-19.17	2
2D4	0.164	-17.90	-29.6 -j272.3	9.2	1.9730	-21.33	3
2D5	0.176	-23.65	-10.1 -j276.1	27.3	1.8650	-26.90	

because the oscillator is only switching from the locked mode to the free-running mode. If an RF signal with a frequency that is an integer fraction of the oscillation frequency is used for the excitation, the nonlinear tunnel diode will generate harmonics at the fundamental oscillation frequency. Intuitively, if one of the harmonics coincides with or is close to the oscillation frequency of the circuit, the turn-off time of the excitation signal may not be critical. While the excitation signal is decreasing, the desired signal already exists and if large enough may be amplified and sustained after the excitation ceases. Since a nonlinear, reactive oscillator circuit may act as a divider as well, two thirds of the oscillation frequency can also be used for the excitation. In this case, two thirds generate one third of the excitation frequency, which is then multiplied to produce the desired signal. For larger amplitude oscillators, excitation frequencies may be further away from exact integer fractions of the desired frequency, because the circuits are more stable overall.

III. Experimental Setup

Back tunnel diodes manufactured by Metelics Co. were used for the experiment. The diode characteristics and oscillator configuration are described in [11]. Several one-diode and two-diode oscillators were designed at 2 GHz for oscillation amplitudes between 0.136 V at which maximum power output occurs, and 0.176 V at which large signal negative conductance almost vanishes [11, Tables I and II]. In Tabls I and II, loss due to the series resistance of the diode was taken into account when the output power was calculated. The distance between the two diodes was limited by the diode package to about 0.5 mm. For two-diode oscillators, the distance between the packages was taken into account for impedance calculations, and the output power was calculated as twice that of the corresponding one-diode oscillator.

The experimental set-up is shown schematically in Fig. 3. An HP 8350B sweep oscillator with an HP 83592C plug-in was used as an external RF source. The turn-off time of the RF signal for this generator is 20–50 ns, depending on the frequency and the power of the signal. The RF excitation is applied to the oscillator circuit through a circulator. The dc bias voltage was applied through a bias-T network, and the dc current was monitored during the experiment. The oscillator signal was detected by an HP 8562A spectrum analyzer. The loss between the signal generator and the oscillator is about 2 dB, and between the oscillator and the spectrum analyzer it is about 3 dB. This setup is very similar to that of the reflection injection-locking scheme [14]. However, the major difference is that in this experiment the excitation signal is applied only for several seconds. The oscillator is not necessarily injection-locked to the external RF signal during the excitation. Once initiated, the output signal of the oscillator is completely independent of the excitation signal power and frequency.

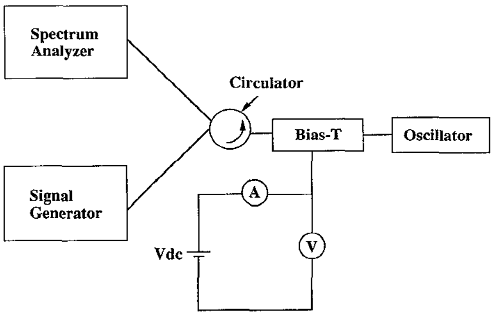

Fig. 3. Schematic diagram of the experimental setup. The external RF signal was applied only for several seconds.

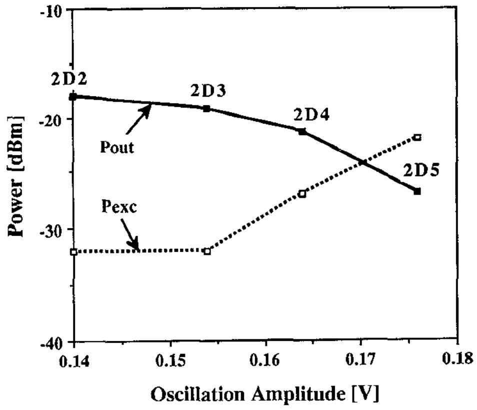

Fig. 4. Output power (solid line) and minimum required excitation power for fundamental frequency excitation (dotted line) for oscillators 2D2–2D5 as a function of the oscillation amplitude.

IV. Fundamental Frequency Excitation

A dc voltage of 0.33 V, sufficient to bias both diodes in the middle of the NDR region, was applied to each two-diode oscillator. As a result of dc instability, both diodes were initially biased in the PDR region, one at 0.01 V and the other at 0.32 V, with 0.1 mA of bias current. An RF signal with frequency close to the expected oscillation frequency of 2 GHz was applied for several seconds. During excitation, the bias current increased to 0.23 mA and the oscillation signal appeared. After turning the excitation signal off, the oscillation was present in all circuits, except for circuit 2D1, which indicates that its designed oscillation amplitude was below the amplitude cutoff level required for sustained oscillation [7], [8]. The oscillation frequency and output power for oscillators 2D2–2D5 is shown in Table II. After excitation, the bias voltage was slightly increased to maximize the output power. Circuit 2D5 had the largest discrepancy, 6.7%, between the designed and measured oscillation frequencies. This circuit was designed for a very large oscillation amplitude and consequently generated large harmonics that were not accounted for in the design [13]. A full harmonic balance method such as the one described in [15] should be used for a more accurate design for very large oscillation amplitudes.

Successive triggering by tuning the bias voltage was only possible with circuit 2D5. As the bias voltage was gradually increased, one diode started to oscillate; this oscillation then excited the second diode as bias was further increased. RF excitation was not necessary for this circuit. Successive triggering can only happen for very large oscillation amplitudes and a small number of diodes connected in series [8]. If more diodes are connected in series, it is harder to satisfy the large signal oscillation condition for all successive cases.

The minimum required excitation power was found to be a strong function of the oscillation amplitude. Fig. 4 shows the output power (solid line) and minimum required excitation power (dotted line) for oscillators 2D2–2D5. For relatively small oscillation amplitude circuits (2D2 and 2D3) only −32 dBm was necessary for excitation, which is 13–14 dB lower than the output power of these oscillators. For higher oscillation amplitude circuits, higher excitation power was required. For the circuit designed for the largest oscillation amplitude (2D5), the required excitation power was about 5 dB higher than the output power. Larger amplitude oscillators have a higher ratio of imaginary to real part of the total diode impedance (X_d/R_d), and therefore higher external quality factors (Q_{ext}) are expected [14, tables I and II]. Circuits with higher Q_{ext} are harder to perturb, and hence larger excitation power is required. Also, circuits designed for a larger oscillation amplitutde have a higher reflection coefficient (initially, when both diodes are biased in the PDR region), and therefore less power is delivered to the diodes. After reflection is taken into account, circuit 2D5 required 5 dB higher power delivered to the diodes than ciruit 2D2.

Excitation was possible over a broader frequency band centered on the oscillation frequency for circuits with higher oscillation amplitudes. For circuit 2D2, the excitation bandwidth was 80 MHz, or 4%, whereas for circuit 2D5, the excitation bandwidth was about twice as wide, 158 MHz, or 8.5%. With the excitation frequency very close to the oscillation frequency, the oscillator was injection-locked to the external RF during excitation, and the total power was lower than the power of the free running oscillator. With the excitation frequency at the edge of the excitation band, the external RF signal, the oscillation signal, and their mixing products were present during excitation, and the oscillation signal remained unchanged after the excitation was turned-off. If the excitation frequency is further away from the oscillation frequency, it will take more time for the oscillator to reach steady state after the excitation is turned off. During this time, discrepancy between bias points of individual diodes may increase sufficiently to switch them back to the PDR region. From the device point of view, larger oscillation amplitude means that more time is spent in the PDR region during each oscillation period, and hence a larger discrepancy between bias points of the individual diodes can be compensated for. Therefore, for larger amplitude oscillators, the excitation frequency can be further away from the oscillation frequency.

Since the required excitation power is more than 10 dB lower than the output power, a low power device such as a single RTD oscillator may be used as an external RF source. This kind of excitation is much easier to implement experimentally than excitation with a fast electrical pulse [7], [8]. At higher frequencies, quasi-optical techniques such as cross-polarization may be used instead of a circulator to separate the excitation and the oscillation signal [16].

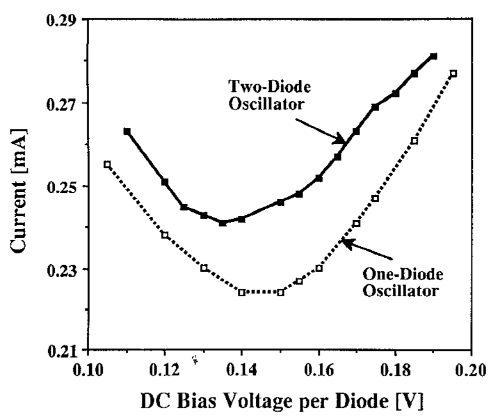

Fig. 5. Measured rectified I–V curve in the NDR region during oscillation, for two-diode oscillator 2D2 (solid line) and one-diode oscillator 1D2 (dotted line). For the two-diode oscillator voltage per diode is shown.

V. Comparison of One- and Two-Diode Oscillators

One-diode oscillators were tested using the same experimental set-up. The measured output power agreed with the predicted values within 1.5 dB, and the oscillation frequency within 3.5% (Table I). Oscillator 1D1 was designed for maximum output power, determined using the procedure described in [13]. Theoretical dc to RF conversion efficiency for circuit 1D1 is 36.8%, whereas 28.2% was measured. The one-diode oscillator corresponding to 2D5 was not tested, because the diode impedance was too low to match to 50 Ω with a single-section quarter-wave transformer.

Two-diode oscillators produced 1–2 dB higher power than the corresponding one-diode oscillators. Due to the diode package there is a phase shift between the diodes, which degrades output power, and hence a full 3-dB increase in power cannot be achieved. Differences between the dc I–V curves of individual diodes also decreases output power. The length of the diode package was not accounted for in this design, and therefore the actual oscillation amplitude is probably somewhat larger (and output power lower) than predicted for the two-diode circuits.

The Q_{ext} was determined for all circuits using the injection-locking technique described in [14]. Higher oscillation amplitude circuits have higher Q_{ext} as expected. However, for one-diode oscillators, measured Q_{ext} is much higher than that predicted by X_d/R_d (Table I). There are several possible reasons for this discrepancy, such as inaccuracy in determining injection-locking power, a difference between designed and realized circuit impedance, and a transmission-line nature of the load.

For two-diode oscillators, using the same injection-locking formula [14], Q_{ext} appeared to be at least two times higher than that for the corresponding one-diode oscillators (their ratio, Q_R, is given in Table II). However, the device line for two-diode oscillators is limited by the oscillation amplitude cut-off, and hence the smaller observed lock-in frequency range (higher Q_{ext}) was probably the result of the shorter device line. Also, due to a difference between designed and realized impedance matching, two-diode oscillators may have higher oscillation amplitude than one-diode oscillators.

During oscillation, rectified I–V curves were measured in the NDR region for one-diode and two-diode oscillators. Rectified I–V curves for circuit 2D2 and the corresponding one diode oscillator 1D2 are shown in Fig. 5, with half of the voltage for the two diode oscillator. These two curves are very similar, which indicates that the two diodes are oscillating simultaneously. Measured rectified I–V curves do not follow the shape of the calculated one (Fig. 2), because during the measurement the oscillation amplitude varied as the dc bias voltage was changed.

Sideband noise was measured using a spectrum analyzer for all oscillators, and it was −94 to −98 dBc/Hz at 100 kHz away from the signal. No improvement in noise performance was observed for two-diode oscillators over one-diode oscillators, and the noise level did not depend on the oscillation amplitude.

VI. Subharmonic Excitation

From the fundamental frequency excitation experiment, the oscillation frequency was determined for two-diode oscillators 2D2–2D5. A dc voltage sufficient to bias both diodes in the middle of the NDR region was applied, and excitation was attempted with two thirds, one half and one third of the oscillation frequency and lower. Subharmonic excitation was not possible for circuit 2D2, which was designed for the smallest oscillation amplitude. Circuits 2D3 and 2D4 had a similar behavior, with the lowest excitation frequency being one third of the oscillation frequency. For circuit 2D5, the lowest excitation frequency was below one sixth of the oscillation frequency, at 290 MHz with −3 dBm. At three fourths, four fifths and five sixths of the oscillation frequency, successful excitation was also observed for this circuit.

Fig. 6 shows the output spectrum during excitation with one third (Fig. 6(a)), one half (Fig. 6(b)), and two thirds (Fig. 6(c)) of the oscillation frequency, and the output spectrum after the excitation signal was turned-off (Fig. 6(d)) for circuit 2D3. The lowest usable excitation power for this circuit was −22 dBm for one third, −27 for one half and −19 dBm for two thirds of the oscillation frequency, which is 3 dB lower, 8 dB lower, and equal to the output power, respectively. During excitation with one third and one half of the oscillation frequency (with power levels given above), the oscillation signal was present, and its frequency and amplitude were the same as after the excitation signal was turned-off. During the excitation with two thirds of the oscillation frequency the oscillation signal was not present.

Similarly to fundamental frequency excitation, as oscillation amplitude increased excitation was possible in larger frequency bands around subharmonic frequencies. Shaded areas in Fig. 7 show the excitation frequency and power ranges for which 100% repeatable excitation was possible for circuits 2D3 (Fig. 7(a)) and 2D5 (Fig. 7(b)). For circuit 2D3, 100% repeatable excitation was possible in very narrow frequency bands, 20 MHz around one half, 10 MHz around one third, and 5 MHz around two thirds of the oscillation frequency. For circuit 2D5, these frequency bands were considerably wider, 60 MHz around one half, 110 MHz around one third, and 300 MHz around and above two thirds of the oscillation frequency.

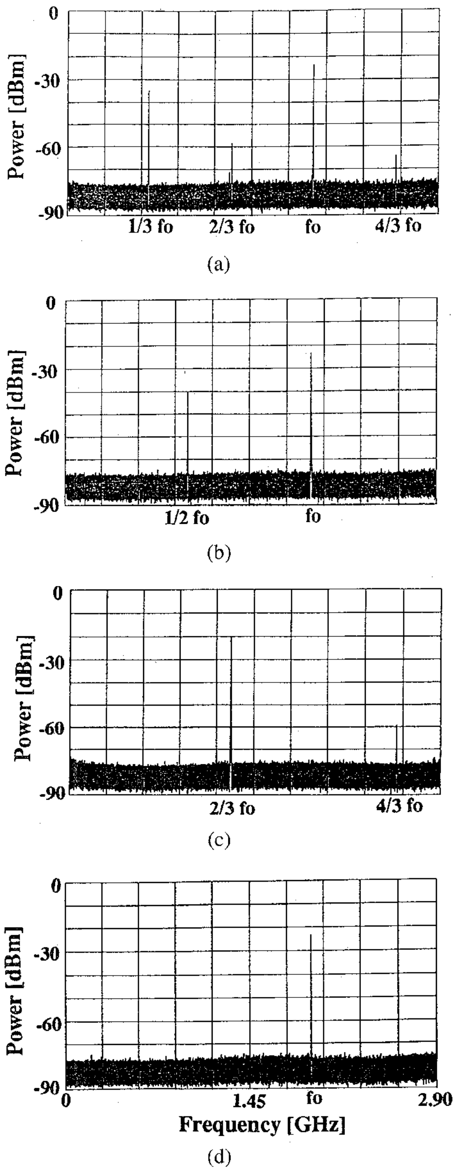

Fig. 6. Spectra during subharmonic excitation with (a) one third, (b) one half, and (c) two thirds of the oscillation frequency for circuit 2D3, and (d) spectrum of the generated signal. Incident powers are −22, −27, and −17 dBm, respectively, with output power −23 dBm, and 1.933 GHz. Actual output power is about 3 dB higher than shown, due to the losses in the experimental set-up. After excitation, bias voltage was slightly increased to maximize the output power.

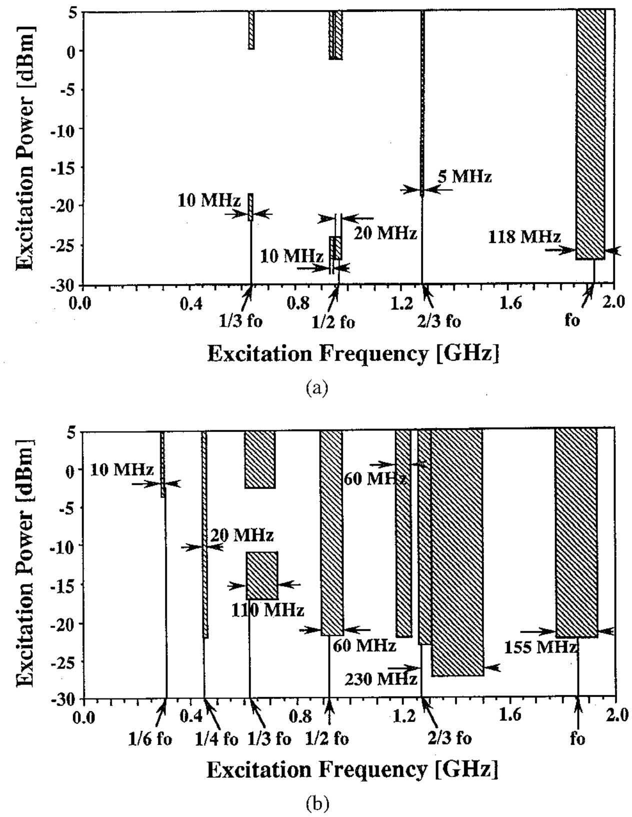

Fig. 7. Observed excitation frequency and power ranges (shaded areas) for 100% repeatable excitation for (a) circuits 2D3 and (b) 2D5. For circuit 2D3, f_o is 1.932 GHz, and for circuit 2D5, f_o is 1.865 GHz. For frequencies in between shaded areas excitation was possible, but it was not 100% repeatable.

Excitation was also possible in between these frequency bands for both circuits, but it was not 100% repeatable. Further away from the shaded areas, the probability of excitation was lower. For circuit 2D5, at frequencies in between 1.2 and 1.5 GHz it seemed that excitation bands around two thirds, three fourths, four fifths and five sixths of the oscillation frequency overlapped.

Strong power dependence of the excitation was observed for circuit 2D3 at one half and one third of the oscillation frequency (Fig. 7(a)). For low excitation power, oscillation was present and independent of the external RF signal during the excitation. For high excitation power, the oscillator was locked to the harmonic of the external RF signal during the excitation. For power in between the shaded areas excitation was still possible, but it was not 100% repeatable. Further away from the shaded areas, the probability of excitation was lower. For circuit 2D5 power dependence was observed only at one third of the oscillation frequency (Fig. 7(b)), and excitation was not repeatable over a much smaller power range than for circuit 2D3. Similarly to fundamental frequency excitation, the larger oscillation amplitude circuit 2D5 required 5 dB higher minimum excitation power at one half and one third of the oscillation frequency than circuit 2D3. With one fourth of the oscillation frequency, 455 MHz, excitation was possible with low power, −22 dBm.

Due to the multi-frequency nature of subharmonic excitation, transient processes are more complicated than for fundamental frequency excitation. Therefore, more robust circuits having a larger oscillation amplitude are more likely to be successfully excited. The circuit designed for the highest output power (for the lowest oscillation amplitude above the amplitude cut-off level) required the lowest power excitation power for fundamental frequency excitation (2D2). However, subharmonic excitation was not possible for this circuit. If subharmonic excitation is required, some power has to be sacrificed for a larger oscillation amplitude. Therefore, there is a trade-off between the oscillator output power and the excitation frequency.

Subharmonic excitation may be a very useful way to initiate the oscillation at high frequencies, where signal sources are not readily available. The required power is not much higher than

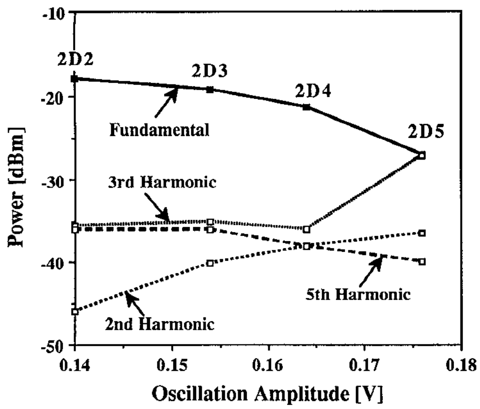

Fig. 8. Fundamental and harmonic power levels for oscillators 2D2–2D5, as a function of the oscillation amplitude. The fourth harmonic was not observed in any circuit, possibly due to the circulator loss.

that for fundamental frequency excitation. For circuit 2D3 the required power was 5 dB higher for excitation with one half of the oscillation frequency than for the fundamental frequency excitation, which is still 8 dB lower than the output power. At higher frequencies, quasi-optical filters may be used instead of a circulator to separate the excitation and the oscillation signal [17].

VII. Harmonic Generation

For the dc bias point in the middle of the NDR region, the dc I–V curve of the tunnel diode appears to have odd symmetry. At large oscillation amplitudes, high nonlinearity is encountered, and consequently large harmonics are generated. Odd harmonics are expected to be larger than even harmonics, due to the odd symmetry of the I–V curve. In this experiment, the oscillator circuits were not optimized for harmonic generation, but large harmonics were still observed. Circulator loss was measured and accounted for, since harmonic frequencies were outside the circulator bandwidth of 1–3 GHz.

Harmonic levels for two-diode oscillators 2D2–2D5 are shown in Fig. 8, as a function of the oscillation amplitude. The fourth harmonic was not observed in any circuit, possibly due to the circulator loss. The third harmonic was stronger than the second in all circuits. Output power of the fifth harmonic was comparable to the third harmonic in circuits 2D2–2D4, and all harmonics were at least 15 dB lower in power than the fundamental. In circuit 2D5, the third harmonic was almost at the same power level as the fundamental. Maximum power for stable oscillation for two diodes in series (obtained for circuit 2D2) is only 9 dB higher than the power of the third harmonic in large amplitude oscillator 2D5.

Harmonic extraction may be useful for generating very high frequencies, in the terahertz range, if high frequency RTD's are used for the oscillator. If less than one sixth of the oscillation frequency is used for the excitation, and the third harmonic is extracted, a signal at almost twenty times the excitation frequency may be generated. If the RTD described in [18] is used, about 1 μW can be obtained from a single diode at 400 GHz. The series integration scheme proposed in [7] (ten diodes integrated in series with the integrated device area increased ten times as compared to the single diode area) may increase this power to 100 μW. If the third harmonic is extracted, assuming that 10 dB less power than the fundamental can be obtained, 10 μW at 1.2 THz may be generated. More power can be obtained by using quasi-optical power combining circuits such as a grid multiplier [19].

VIII. Conclusion

Connecting several tunneling diodes in series was shown to be a feasible method for increasing the output power of these devices as oscillators. The excitation of such an oscillator using an RF source was demonstrated in a proof-of-principle experiment, for a 2-GHz oscillator with two tunnel diodes connected in series. The excitation was successful both with excitation frequency close to as well as considerably lower than the oscillation frequency. Excitation with frequency as low as one sixth of the oscillation frequency was achieved. Very low power was required for both fundamental frequency excitation and excitation at one half of the oscillation frequency. For one circuit (2D3), the power required for fundamental excitation was 13 dB lower than the oscillator output power, whereas for excitation at one half of the oscillation frequency it was 8 dB lower than the oscillator output power. Excitation with one third of the oscillation frequency and lower required more power. Circuits that oscillate with larger amplitudes can be excited in broader frequency bands around subharmonics. Both fundamental and subharmonic excitation are much easier to implement experimentally than the alternative fast pulse excitation. Due to the highly nonlinear dc I–V curve of the tunnel diode, strong harmonics were generated in the circuit which oscillated with a very large amplitude. A third harmonic almost as strong as the fundamental was observed in that circuit. If high frequency series integrated RTD's are used for the active device, and the third harmonic is extracted, signal generation at terahertz frequencies may be possible.

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