DC Instability of the Series Connection of Tunneling Diodes

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Abstract—**An oscillator with a series connection of tunneling diodes produces significantly higher power than a single diode oscillator. However, a circuit with series-connected tunneling diodes biased simultaneously in the negative differential resistance (NDR) region of the I–V curve is dc unstable. This dc instability makes the series connection oscillator fundamentally different from a single diode oscillator. Associated with the dc instability are the phenomena of minimum oscillation amplitude and frequency. Due to the minimum oscillation amplitude, it is critical to provide the impedance match between the oscillator circuit and the series connection at the desired oscillation amplitude level. An in depth, comprehensive analysis of the dc instability is given here. Based on this analysis, a numerical procedure is developed to accurately predict the minimum oscillation amplitude and frequency. Time domain simulations which give further insight into series-connection oscillator behavior are discussed. The effect of increasing the number of diodes on the oscillator performance is explored as well. Based on numerical and simulation results, oscillators with several tunnel diodes connected in series were designed and tested. Experimental results that confirm the existence of the minimum oscillation amplitude are presented for oscillators with two, three, and four tunnel diodes.**

I. Introduction

A resonant tunneling diode (RTD), currently the fastest room temperature solid-state active device, is considered to be a promising millimeter- and submillimeter-wave source. However, RTD oscillators reported so far have not produced useful power levels. The maximum power generated by an RTD oscillator at microwave frequencies to date is 20 mW at 2 GHz [1]. At submillimeter frequencies, 0.2 μW at 420 GHz with a GaAs/AlAs diode [2], and 0.3 μW at 712 GHz with an InAs/AlSb diode were reported [3]. Only if the power levels generated by these diodes are increased, will RTD's be useful in practical applications. Besides the fundamental thermal and impedance constraints [4], the output power from a single RTD oscillator is also limited by stability considerations [5]. To meet typical system requirements, it would be necessary to combine the output power from several RTD's. Several power-combining schemes have been proposed for oscillators using tunneling diodes (the term "tunneling diode" will be used to refer to an RTD or a p-n tunnel diode). For example, a modification of the Kurokawa–Magalhaes combiner was used to combine the power from two RTD oscillators at 75 GHz [6]. The parallel connection of 25 RTD's was successfully used to generate 5 mW at 1.18 GHz [7]. Quasi-optical power combining was also proposed based on an RTD oscillator with a slot-coupled quasi-optical open resonator [8]. A 16-element tunnel diode grid oscillator successfully operated at 2 GHz [9]. The series connection of tunnel diodes in order to increase the oscillator output power was proposed and successfully demonstrated at low frequencies in 1965 by Vorontsov and Polyakov [10]. The series integration of RTD's in order to enhance the output power of an RTD oscillator at millimeter-wave frequencies was proposed by Yang and Pan [11].

An oscillator with several tunneling diodes connected in series produces significantly higher power than a single diode oscillator, but that is not the only difference between the two oscillators [10], [11]. Due to the negative differential resistance (NDR) region in the dc I–V curve of a single tunneling diode, a circuit using several tunneling diodes biased simultaneously in the NDR region and connected in series is dc unstable. This means that if there is no RF signal present in the circuit, the diodes cannot stay biased simultaneously in the NDR region. However, if there is an RF signal present, the bias points may be maintained simultaneously in the NDR region (the circuit may be RF stable), provided that the RF signal satisfies certain conditions. Owing to the dc instability, the design of an oscillator with a series connection is much more involved than just determining the impedance of several diodes in series. A simple dc battery is insufficient to bias several tunneling diodes simultaneously in the NDR region. Associated with the dc instability are the phenomena of minimum oscillation amplitude and frequency. Due to the minimum oscillation amplitude, it is critical to provide the impedance match between the oscillator circuit and the series connection at the desired oscillation amplitude level.

An in depth, comprehensive analysis of the dc instability is given in this paper for the piece-wise continuous, linear approximation of the tunneling diode I–V curve. The existence of minimum amplitude and frequency was recognized in [10], and their values were estimated numerically in [11]. In this paper, the minimum oscillation amplitude and frequency are physically explained and analytically derived based on the dc instability analysis. A numerical procedure is developed to accurately predict these two parameters. MWSpice simulations which give further insight into series-connected tunneling diode oscillator behavior are discussed. The effect of increasing the number of diodes on oscillator performance is explored as well. Based on numerical and simulation results, oscillators

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with several tunnel diodes connected in series were designed and tested. Experimental results that confirm the existence of minimum oscillation amplitude are presented for oscillators with two, three, and four tunnel diodes.

II. DC INSTABILITY

In the following analysis, we will consider two tunneling diodes connected in series and biased with one dc battery [Fig. 1(a)]. First we assume an RF signal present in the circuit, and analyze the stability of the difference between the total voltages on individual diodes (diode operating points). Next we analyze the dc bias distribution if there is no RF signal present. Each diode is represented as a parallel connection of a capacitance and a voltage controlled current source. A series resistance is not taken into account to simplify the analysis. Diodes are assumed to have the same capacitance and identical I–V curves. For the purpose of this discussion, a piece-wise continuous linear approximation of the dc I–V curve may be used [Fig. 1(b)]. In the NDR region, the slope of the I–V curve is $-R_n^{-1}$, where R_n^{-1} is positive. For simplicity, we can assume that the slope of the I–V curve in the positive differential resistance (PDR) regions, R_p^{-1}, is the same on the first and second rising branches. Ideally, since the diodes are identical, the total applied dc and RF voltage should be equally divided between the two diodes. However, due to device noise [12], there is always a small difference between individual diode voltages, $\Delta V_d(t)$

$$\Delta V_d(t) = V_{d1}(t) - V_{d2}(t). \tag{1}$$

Initial amount of noise $\Delta V_d(0)$ can be estimated from the device physics

$$\Delta V_d(0) = \Delta V_{d0}. \tag{2}$$

If there is no RF signal present in the circuit, the total instantaneous voltage will be equal to the applied dc bias voltage

$$V_{d1}(t) + V_{d2}(t) = V_{dc}. \tag{3}$$

Differentiating (3), we obtain

$$\frac{dV_{d1}(t)}{dt} + \frac{dV_{d2}(t)}{dt} = 0. \tag{4}$$

In this case, we can assume that the initial bias distribution is

$$V_{d1,\,2}(0) = \frac{V_{dc} \pm \Delta V_{d0}}{2}. \tag{5}$$

For both diode operating points on the first or on the second rising branch (R_p) or in the NDR region (R_n), the differential equation for the total current reduces to (Fig. 1)

$$C\frac{dV_{d1}}{dt} \pm \frac{V_{d1}}{R_{p,\,n}} = C\frac{dV_{d2}}{dt} \pm \frac{V_{d2}}{R_{p,\,n}}. \tag{6}$$

Substituting (1) into (6), we obtain the differential equation for ΔV_d, which using the initial condition (2) gives the solution

$$\Delta V_d(t) = \Delta V_{d0} e^{\mp(t/R_{p,\,n}C)}. \tag{7}$$

If there is no RF signal present, (3) and (4) can be substituted into (6). Rearranging the terms, differential equations for

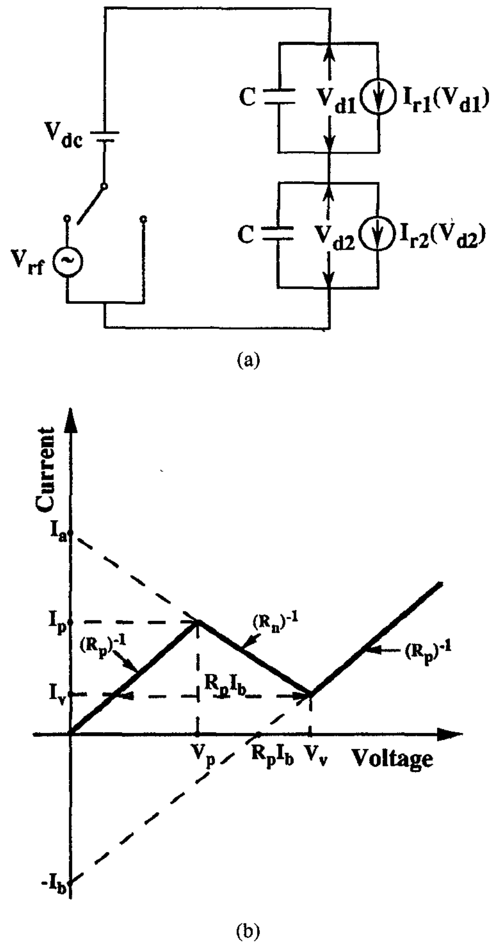


Fig. 1. Simplified model of an oscillator with two tunneling diodes in series (a) and a piece-wise continuous linear approximation of the dc I–V curve of a single tunneling diode (b).

$V_{d1}(t)$ and $V_{d2}(t)$ can be obtained, which using the initial condition (5) give solutions

$$V_{d1,\,2}(t) = \frac{V_{dc}}{2} \pm \frac{\Delta V_{d0}}{2} e^{\mp(t/R_{p,\,n}C)}. \tag{8}$$

Therefore, if both diode operating points are on the first or on the second rising branch, any difference between diode voltages due to noise will decrease proportionally to the diode R_pC constant (7). If there is no RF signal, the bias voltage in the range $V_{dc} \leq 2V_p$ and $V_{dc} \geq 2V_v$ will be equally divided between the diodes. In this case the bias distribution is dc stable, since any initial difference decreases in time and eventually vanishes (8). Any time two or more diodes are biased simultaneously in the NDR region, if no RF signal is present but there is a difference in bias voltages due to noise, this difference will grow proportionally to the diode R_nC constant (8). Given that both diodes were initially biased close to the middle of the NDR region, the diode bias points will switch to the PDR region when the difference in bias voltages becomes equal to the extent of the NDR region. Therefore, having both diodes biased simultaneously in the NDR region is an unstable solution for the bias distribution. However, if an RF signal is present, bias points can be maintained simultaneously in the NDR region.

If one diode's operating point is on the first rising branch, and the other on the second rising branch, and if the diode bias points are in the NDR region, the diodes must be oscillating out of phase. However, it is impossible for the diodes to oscillate out of phase and have the same total current. Therefore, in this case, the difference between diode operating points will become the difference between dc bias points. Assuming that the operating point of diode one is on the first rising branch and of diode two on the second rising branch, differential equation for the total current becomes

$$C\frac{dV_{d1}}{dt}+\frac{V_{d1}}{R_p}=C\frac{dV_{d2}}{dt}+\frac{V_{d2}}{R_p}-I_b. \tag{9}$$

Using (3) and (4), and rearranging the terms, differential equations for $V_{d1}(t)$ and $V_{d2}(t)$ can be obtained. Assuming that diode one is initially biased at the peak voltage, and diode two at the valley voltage, we can find solutions given by

$$V_{d1,2}(t)=\frac{V_{dc}}{2}\mp\frac{I_bR_p}{2} \pm\left(\frac{I_bR_p}{2}-\frac{V_v-V_p}{2}\right)e^{-(t/R_pC)}. \tag{10}$$

Since the quantity in brackets in (10) is always positive [Fig. 1(b)], $V_{d1}(t)$ will decrease, while $V_{d2}(t)$ will increase until they reach the equilibrium values. At this point conduction currents are equal. If the equilibrium voltages found from (10) are perturbed, solving (9) gives the solutions

$$V_{d1,2}(t)=\frac{V_{dc}}{2}\mp\frac{I_bR_p}{2}\mp\frac{\Delta V_{d0}}{2}e^{-(t/R_pC)}. \tag{11}$$

Therefore, this bias voltage distribution is dc stable, since it returns to the initial value if perturbed. However, if an RF signal is applied externally to the diodes, and if the slopes of the first and second branch of the dc I–V curve are nonlinear and not equal, this bias distribution may be RF unstable [13], [14].

This analysis may be extended for additional diodes connected in series. Furthermore, assuming a nonlinear dc I–V curve, implies that R_n and R_p are not constant, and the differential equations must be solved numerically. However, the same qualitative conclusions as for the piece-wise continuous dc I–V curve case will still hold.

The biasing problem can be explained from this dc stability analysis. As the bias voltage is increased slowly from zero to $2V_p$, both diodes will be biased on the first rising branch, and bias voltage will be equally divided between the diodes. As soon as diodes are simultaneously biased in the NDR region, if there is any difference in individual bias voltages ΔV_d due to noise, this difference will start growing. Effectively, bias voltage will be increasing on one diode, and decreasing on the other diode (7). Hence, the rate of the increase of the bias voltage must be greater than the rate of increase of ΔV_d, so that the voltage at each tunnel diode may be increased as well. Otherwise, if the rate of increase of bias voltage is slow compared to the diode R_nC time, the diode bias points will switch to the PDR region. If a dc bias voltage sufficient to bias all tunneling diodes in the middle of the NDR region is applied gradually, the dc instability will divide this voltage

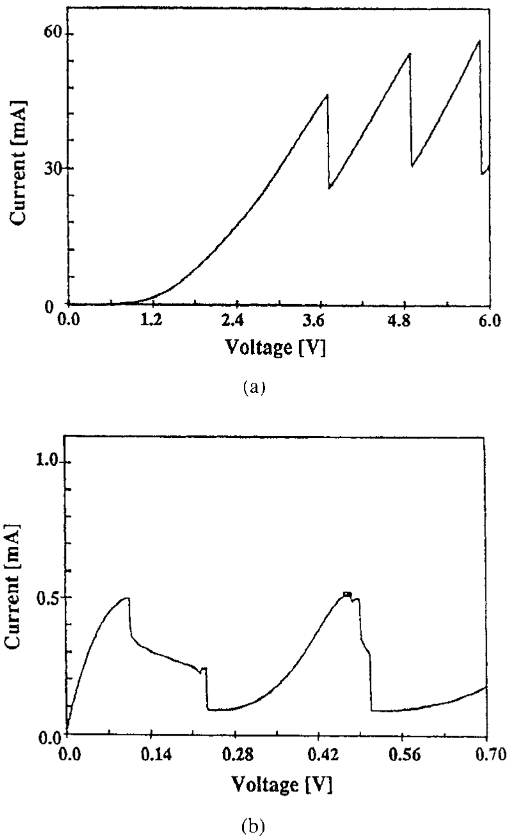


Fig. 2. DC I–V curve of (a) three vertically integrated RTD's for 50 μm diameter device and (b) two series connected tunnel diodes (back diodes M1X1168 manufactured by Metelics Co.), measured using an HP 4145 curve tracer. Due to the dc instability, multiple current peaks are observed.

so that all the diodes are biased in the PDR region. The dc I–V curve of the series connection exhibits multiple peaks, because the diodes cannot simultaneously be biased in the NDR region. Fig. 2 shows the dc I–V curve of (a) three vertically integrated RTD's for 50 μm diameter device and (b) two series connected tunnel diodes (back diodes M1X1168 manufactured by Metelics Co.), measured using an HP 4145 curve tracer. There are several effective solutions to the biasing problem: fast electric pulse excitation [10], RF excitation [13], [14], optical illumination [15], and successive triggering [10], [14].

Besides the biasing problem, oscillation amplitude and frequency limitations are important consequences of the dc instability as well. Both of these phenomena stem from keeping diode bias points simultaneously in the NDR region during oscillation, as will be explained in the following sections.

III. Minimum Oscillation Amplitude

A signal generated by a single tunneling diode oscillator may be of any amplitude smaller than the maximum oscillation amplitude $(V_{rf})_{\max}$ at which the negative differential conductance becomes zero [13]. For a series connection oscillator, if the oscillation amplitude is so small that the diode operating points remain in the NDR region during the whole oscillation period, the difference between diode voltages will be steadily increasing (7). When this difference becomes comparable to the extent of the NDR region, diode bias points will switch to the PDR region and the oscillation will cease. If the oscillation amplitude is large enough so that during each oscillation period diode operating points cross to the PDR region, oscillation may be maintained. During the time diode operating points are in the PDR region, the difference between diode voltages decreases (7) canceling some of the increase that occurred in the NDR region. To maintain the oscillation, the oscillation amplitude must be large enough to cover a portion of the PDR region sufficient to cancel the growth of the difference between diode voltages, ΔV_p, during each period (7)

$$\Delta V_{d0} e^{t_n/R_nC} e^{-(t_p/R_pC)} \leq \Delta V_{d0} \tag{12}$$

where t_n and t_p are the times spent in the NDR and PDR region respectively during one oscillation period. For better accuracy, nonlinear I–V curves can be divided into small segments where a linear I–V relationship can be established. Assuming that $-G_{ni}$ is the slope of ith segment in the NDR region, and G_{pj} the sum of the slopes of jth segments in the two PDR regions, (12) can be simplified as

$$\sum_1^k G_{ni} \leq \sum_1^m G_{pj} \tag{13}$$

where k is the known number of segments in the NDR region, and m is the number of segments in the PDR regions to be determined from (13). When (13) is satisfied, minimum oscillation amplitude can be calculated as

$$(V_{rf})_{\min} = \frac{k+m}{2} \cdot \Delta V \tag{14}$$

where ΔV is the voltage segment. Equation (14) was derived for the steady-state oscillation (12), without taking into account the amount of noise that accumulates during oscillation build-up. In reality, minimum amplitude will be somewhat higher, and it will slightly depend on the oscillator configuration and type of excitation. For relatively low frequencies, minimum oscillation amplitude is also related to the oscillation frequency, as will be shown in the following section.

For a single tunneling diode oscillator, due to a broad range of values of negative resistance and the absence of a low frequency limitation, an oscillation is likely to occur even if impedance matching is not very accurate, but output power may be very low. However, in the case of an oscillator with several tunneling diodes in series, without appropriate impedance matching, oscillation is not possible at all. Due to the minimum oscillation amplitude, it is critical to provide the impedance match between the oscillator circuit and the series connection at the desired oscillation amplitude level.

IV. Minimum Oscillation Frequency

For a single tunneling diode oscillator, oscillation is possible at any frequency below the high frequency cutoff f_c (frequency at which the real part of the diode impedance becomes zero [4], [5]). In the case of a series-connection oscillator, there is also a lower limit on the oscillation frequency. At lower frequencies, oscillation period is longer, and diode operating points spend more time in the NDR region. During the time diode operating points are in the NDR region, the difference in diode voltages ΔV_d increases (7). If this difference becomes comparable to the extent of the NDR region, the diode bias point will switch to the PDR region and the oscillation will cease. During one oscillation period, the NDR region is swept twice, and the time spent in the NDR region continuously without crossing to the PDR region is one half of the total time spent in the NDR region, t_n. Therefore, using (7), the maximum time that can be spent in the NDR region during one oscillation period, $(t_n)_{\max}$, can be found from the following equation

$$\Delta V_{d0} e^{(t_n)_{\max}/2R_nC} = V_v - V_p. \tag{15}$$

For nonlinear I–V, divided into small linear segments, (15) can be modified as

$$\Delta(t_n)_{\max} = \frac{2C}{\sum_1^k G_{ni}} \cdot \ln\left(\frac{V_v - V_p}{\Delta V_{d0}}\right) \tag{16}$$

where

$$(t_n)_{\max} = k\Delta(t_n)_{\max}. \tag{17}$$

To find the minimum oscillation frequency, we also need to know the ratio of the time spent in the NDR region to one oscillation period. Oscillation amplitude determines this ratio, and for each amplitude a corresponding minimum frequency can be found. As the oscillation amplitude increases, more time is spent in the PDR region and a smaller portion of the period is spent in the NDR region, so the minimum frequency will be lower. The maximum oscillation amplitude $(V_{rf})_{\max}$ determines the lowest of the minimum frequencies. For $(V_{rf})_{\max}$, the minimum ratio of time spent in the NDR region to one oscillation period can be found (Fig. 3)

$$(V_{rf})_{\max} \sin\left[\frac{\pi}{2}\left(\frac{t_n}{T}\right)_{\min}\right] = \frac{V_v - V_p}{2}. \tag{18}$$

Using (16)–(18), the minimum oscillation frequency can be determined as

$$f_{\min} = \frac{\left(\frac{t_n}{T}\right)_{\min}}{(t_n)_{\max}}. \tag{19}$$

On the other hand, at very low frequencies, the oscillation frequency will determine the minimum oscillation amplitude. If the oscillation period is comparable to $(t_n)_{\max}$, (12) is not valid any more, and (15) should be considered instead. With oscillation frequency known, and with $(t_n)_{\max}$ determined from (17), the minimum oscillation amplitude can be determined using the same reasoning as for (18) (Fig. 3).

Even though multiple NDR regions exist in the dc I–V curve of the series connection, there is a minimum oscillation frequency for the series-connected tunneling diodes. This is because the NDR region, that exists effectively during oscillation, is not what is seen in the dc I–V curve. If all diodes are oscillating simultaneously, the I–V curve of a single diode is effectively stretched N times along the voltage axis,

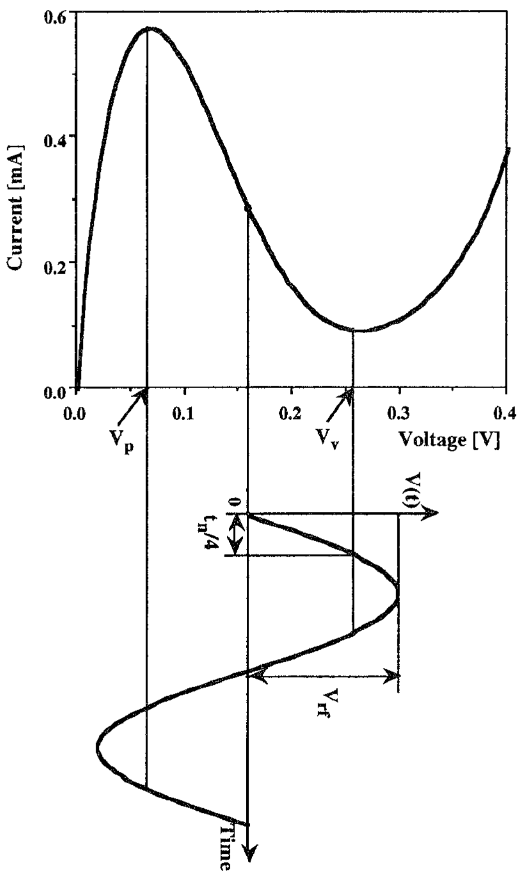


Fig. 3 Oscillation amplitude determines the ratio of the time spent in the NDR region to one oscillation period.

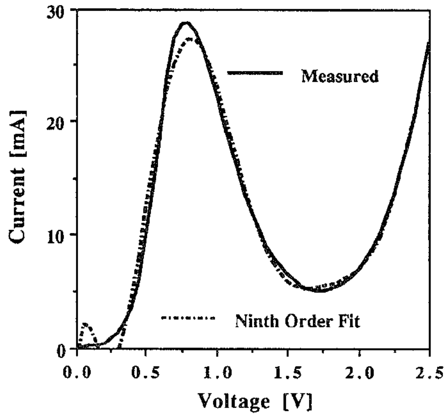


Fig. 4. RTD dc I–V curve and ninth-order polynomial fit.

TABLE I
MINIMUM OSCILLATION AMPLITUDE AND FREQUENCY FOR SERIES CONNECTION OF TUNNEL DIODES AND RTD'S

	MATLAB		MWSPICE	
DIODE	$(V_{rf})_{min}$ [V]	f_{min} [MHz]	$(V_{rf})_{min}$ [V]	f_{min} [MHz]
TUNNEL	0.122	74	0.125	20
RTD	0.60	191	0.63	50

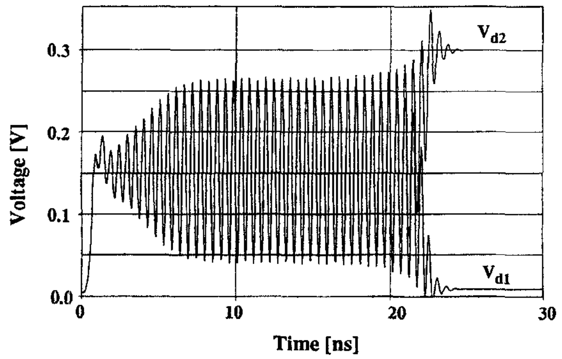
and there is only one NDR region, N times wider than the NDR region of a single diode. Such a "stretched" I–V curve could be observed only if the voltage of a curve tracer was swept at the frequency higher than the minimum oscillation frequency. During oscillation, a small portion of a rectified, stretched I–V curve can be measured [14].

V. SIMULATION RESULTS

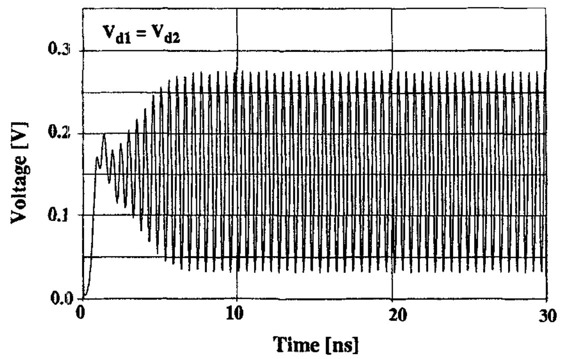
Minimum oscillation amplitude and frequency were calculated for one tunnel diode and one RTD based on the dc instability analysis (14), (19). A low peak current tunnel diode (back diode), M1X1168 manufactured by Metelics Co., is described in [13] (diode's dc I–V in Figs. 2 and 3), and its I–V curve was modeled using the fifth-order polynomial fit. The RTD considered here is an actual diode fabricated at UCLA, described in [16] (diode's dc I–V in Figs. 2 and 4), and its I–V curve was modeled using the ninth-order polynomial fit (Fig. 4). All calculations were done using the Math Works Inc. MATLAB program [17], and results for both diodes are presented in Table I. Initial amount of noise was estimated as Shot noise [12], for bias current in the middle of the NDR region and a bandwidth of 200 MHz, which gave 0.04 mV for the tunnel diode and 0.03 mV for the RTD.

The series-connected diode oscillator behavior was simulated in the time domain using HP-EEsof's Microwave SPICE program [18]. Simulations were done for oscillators with two, three and four tunnel diodes and for oscillators with three RTD's connected in series. The large signal impedance of each diode was calculated using the procedure described in [16], and planar microstrip oscillators were designed at 2 GHz using HP–EEsof's Touchstone program [19]. Circuit impedance was matched to the device impedance at the oscillation amplitude levels above the minimum value determined from the MATLAB calculations. Oscillators were designed as two port networks, with one port used for the excitation and the other for the output.

It was initially verified that the oscillation occurred at the design frequency and amplitude level. Then, circuit parameters were varied to decrease the oscillation amplitude to the value below which oscillation could not be maintained. Fig. 5(a) shows the voltage on each tunnel diode in a two-diode oscillator for the oscillation amplitude below the minimum value. Diodes are initially biased in the NDR region and are oscillating, but after about forty periods the bias points switch to the PDR region [one to the first rising branch (V_{d1}) and the other to the second rising branch (V_{d2}) of the dc I–V curve], and oscillation ceases. Fig. 5(b) shows the voltage on each tunnel diode during stable oscillation (these voltages are equal), with the oscillation amplitude above the minimum value. As the number of diodes was increased in the same oscillator configuration, it was found that the minimum oscillation amplitude increased somewhat, from 0.125 V for a two-diode oscillator to 0.13 V for a four-diode oscillator. Minimum oscillation amplitudes determined from the MWSpice simulation for oscillators with a series



(a)



(b)

Fig. 5. Voltage on each tunnel diode for the oscillation amplitude: (a) below the minimum value and (b) above the minimum value for a two-diode oscillator.

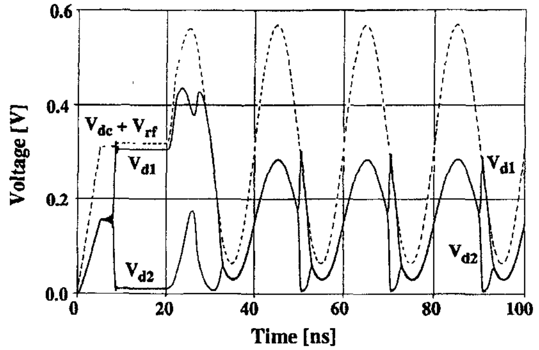


Fig. 6. Excitation voltage and voltage on each tunnel diode for an RF frequency of 50 MHz, and an RF amplitude of 0.125 V on each diode, for a two-diode oscillator.

connection of two tunnel diodes and three RTD's are shown in Table I. These values agree with values obtained from the MATLAB calculations within 5%.

Similar simulations were done to determine the minimum oscillation frequency for the series connection. Diodes were initially biased with a slow pulse, in the PDR regions, and an external RF signal was applied to the oscillator. The frequency of the external RF signal was lowered until diode voltage was not sinusoidal any more. In the case of a two tunnel diode oscillator, for frequencies between 2 GHz and 80 MHz, and an RF voltage amplitude of 0.125 V on each diode, diode bias points were not seen to switch to the PDR region. As the frequency was lowered, the voltage amplitude had to be increased to keep diodes biased in the NDR region. Fig. 6 shows the excitation voltage (dashed line) and voltage on each tunnel diode (solid lines) in a two-diode oscillator for an RF frequency of 50 MHz, and an RF amplitude of 0.125 V on each diode. During the first period of the external RF signal, diode bias points switched to the NDR region, and diode voltages started to follow the sinusoidal external voltage. However, before the end of the second period the diode bias points switched to the PDR region. This was repeated during each consecutive period, with each diode sometimes switching to the low voltage and sometimes to the high voltage. For a 20 MHz RF frequency, the required voltage amplitude on each diode was already 0.2 V, which was above the maximum amplitude for which the diode can be used in an oscillator [13]. Therefore, free-running oscillations at frequencies below 20 MHz cannot exist. In the frequency range between 20 MHz and 80 MHz, oscillations can exist, but only with an oscillation amplitude above the very large minimum amplitude, which is strongly dependent on frequency. Spurious oscillations at frequencies below 20 MHz may exist simultaneously with the desired oscillation signal of much higher frequency, but their frequency and amplitude would also be constrained by the dc instability, which makes them less likely to occur. Using the same procedure, it was determined that the minimum oscillation frequency for a series connection of RTD's is about 50 MHz. Minimum oscillation frequency values obtained from the MWSpice simulations are about three times lower than that obtained from MATLAB calculations (Table I), due to the different initial amount of noise, which is critical for this estimate (15). In MWSpice simulations, only thermal noise in a very narrow bandwidth is taken into account, whereas a more realistic prediction of Shot noise is assumed in MATLAB calculations.

VI. Experimental Results

Due to the high series resistance and the unsuitable diode configuration, it was not possible to use the RTD's in the experiments. Previously described tunnel diodes were used for proof-of-principle experiments. Several two-, three-, and four-diode oscillators were designed at 2 GHz for oscillation amplitudes above the minimum values determined from the simulations. The phase shift between the devices due to the diode package was taken into account for the impedance calculations [20]. Oscillators were fabricated in a one-port configuration, and RF excitation was used to trigger the oscillation [13], [14].

The performance of two-diode oscillators was described in detail in [14]. Neither oscillation nor switching of bias points was observed in the oscillators designed for oscillation amplitudes smaller than 0.14 V. Therefore, it was determined that 0.14 V was the minimum oscillation amplitude, which is about 10% higher than that predicted by the simulations. This discrepancy is reasonable, taking into account that experiment must be "noisier" than the simulation. Also, in the simulation, the diodes were assumed to be identical, whereas it was impossible to avoid some variation in their dc I–V characteristics in the experiment.

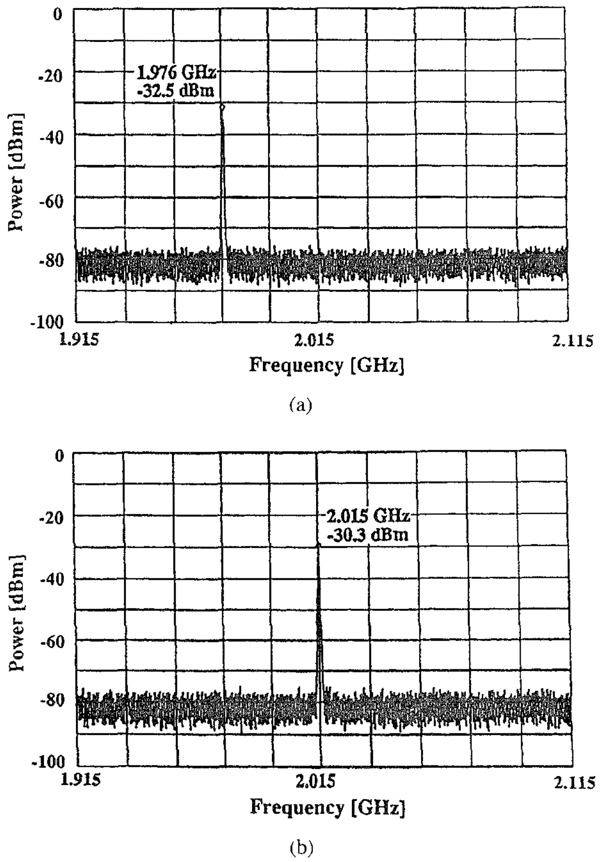


Fig. 7. Output spectrum of the oscillator with four tunnel diodes for an excitation frequency of (a) 1.99 GHz and (b) 2.05 GHz.

Oscillators with three and four diodes were much more difficult to trigger than two-diode oscillators [20]. For oscillation amplitudes below 0.154 V neither switching nor oscillation was observed. Switching of bias points was occurring, but stable oscillation was not possible for the amplitude of 0.154 V in the case of three- and four-diode oscillators. For the oscillation amplitude of 0.176 V, the signal for the three- and four-diode oscillators existed only for a very limited bias voltage range and the output power was barely increased as compared to the two-diode oscillators. For the best three-diode oscillator, the oscillation frequency was 2.001 GHz, with an output power of −27.5 dBm, whereas a comparable two-diode oscillator gave −28 dBm at 1.995 GHz. Some increase in the minimum oscillation amplitude with the increased number of diodes was predicted from the simulation, but not such a drastic difference in the oscillator performance. This could be attributed to the diode separation due to the package, which makes the impedance of the series connection difficult to predict. Also, when the length of the series connection becomes significant compared to the circuit dimensions, generated power is no longer combined strictly on the device level. The four-diode oscillator designed for an oscillation amplitude of 0.176 V exhibited multimode operation characteristic for circuit level power combining [21]. In this case, the oscillator output signal was dependent on the excitation frequency. For an excitation frequency of 1.99 GHz, excitation was possible with power as low as −37 dBm. After the excitation signal was turned off, the oscillation frequency was 1.976 GHz, with an output power of −29.5 dBm [Fig. 7(a)]. For an excitation frequency of 2.05 GHz, much larger excitation power (−7 dBm) was required. In this case, the oscillation frequency was 2.015 GHz, with an output power of −27 dBm [Fig. 7(b)]. It is possible that only three diodes oscillated in a four diode oscillator, especially in a lower frequency mode. A series integrated device, such as proposed in [11], should not be affected by these problems, since the diodes can be placed very close to each other. Therefore, connecting more than two packaged diodes in series does not provide further insight into the behavior of a series integrated device.

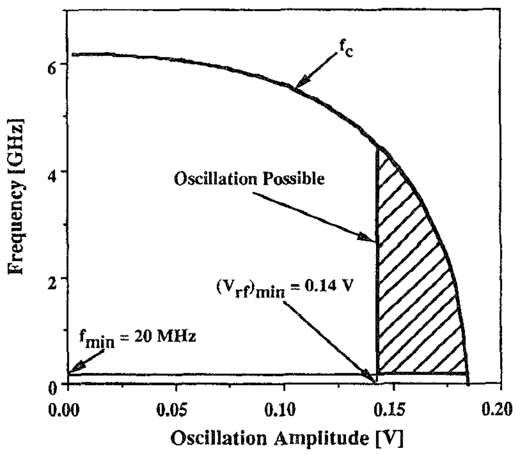


Fig. 8. Possible frequency and amplitude ranges of oscillation for a series connection of tunnel diodes

It was not possible to experimentally determine the minimum oscillation frequency in the way it was done in simulations, because it would be very difficult to determine the voltage amplitude on each diode during excitation. In the simulation, we can easily see at which frequency the voltage amplitude on each diode exceeds $(V_{rf})_{\max}$. In the experiment, it is very difficult to accurately determine how much power is delivered to the diodes during excitation, and the corresponding voltage on each diode, because diode impedances are changing during excitation.

Possible frequency and amplitude ranges of oscillation for a series connection of tunnel diodes are presented in Fig. 8. For a single diode oscillator, an oscillation is possible with any amplitude between 0 V and 0.182 V, provided that the frequency of oscillation is below the high frequency cutoff for that oscillation amplitude. For a series connection, stable oscillation is possible only for the oscillation amplitude above the minimum value, and in a limited frequency band (shaded area in Fig. 8). This makes the oscillator design more challenging, since large signal impedance of the series connection must be determined accurately for successful oscillator operation.

VII. Conclusion

The dc instability of the series connection of tunneling diodes and its consequences, such as the minimum oscillation amplitude and frequency, were analyzed in detail. Based on the dc instability analysis, a numerical procedure was developed to estimate the minimum oscillation amplitude and frequency, and these parameters were calculated for one tunnel diode and one RTD. MWSpice simulations were carried out to give further insight into series-connected diode oscillator behavior. The minimum oscillation amplitude obtained from MATLAB calculations agrees within 5% with results obtained from MWSpice simulations for both diodes. Based on these results, oscillators with two, three, and four diodes were designed and tested. As observed in simulations, the minimum oscillation amplitude increased with the number of diodes in the experiment. Also, three- and four-diode oscillator performance was significantly different from the two-diode oscillator performance, possibly because of the phase shift between diodes due to the package. The four-diode oscillator exhibited a multimode operation characteristic for the circuit level power combining. Therefore, connecting more than two packaged diodes in series does not provide further insight into the behavior of a series integrated device, such as proposed in [11].

The minimum oscillation amplitude makes the series-connection oscillator design more challenging than a single diode oscillator design. For a single tunneling diode oscillator, due to a broad range of values of negative resistance and the absence of a low frequency limitation, an oscillation is likely to occur even if impedance matching is not very accurate, but output power may be very low. However, in the case of an oscillator with several tunneling diodes in series, without appropriate impedance matching, oscillation is not possible at all. Due to the minimum oscillation amplitude, it is critical to provide the impedance match between the oscillator circuit and the series connection at the desired oscillation amplitude level.

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