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DESIGN AND TRIGGERING OF OSCILLATORS WITH A SERIES CONNECTION OF TUNNELING DIODES

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Abstract. A resonant tunneling diode (RTD) is considered to be a promising millimeter- and submillimeter-wave source. It is currently the fastest solid-state active device, with the highest reported frequency of oscillaaon above 700 GHz, but with a very low output power. Connecting several tunneling diodes (RTD's or tunnel diodes) in series was shown to be a feasible method for increasing the output power of oscillator circuits using these devices. In this paper, design and excitation of oscillators with several tunneling diodes connected in series is studied theoretically and experimentally. The DC instability of the series connection of tunneling diodes and its effects on biasing are explained. Several solutions to the biasing problem are discussed. A simple large signal diode analysis is used to calculate negative differential conductance, output power, high frequency cutoff and other parameters as a function of the oscillation amplitude. Based on the large signal analysis, oscillators with several tunneling diodes in series were designed and tested. The biasing problem was successfully solved using an extemal RF source to trigger the oscillation. RF triggering was demonstrated in proof-of-principle experiments at microwave frequencies, for oscillators with several tunnel diodes connected in series.

1. Introduction

A resonant tunneling diode (RTD) is considered to be a promising millimeter- and submillimeter- wave source. It is currently the fastest solid-state active device, but with a very low output power. The maximum power generated by an RTD oscillator at microwave frequencies to date is $20mW$

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at 2 GHz [1]. At submillimeter frequencies, $0.2\mu W$ at 420 GHz with a GaAs/AlAs diode [2], and $0.3\mu W$ 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. As for any other solid state device, the output power from a single RTD oscillator is limited by fundamental thermal and impedance constraints [4]. 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. For example, a modification of the Kurokawa-Magalhaes combiner was used to combine the power from two RTD oscillators at 75 GHz [5]. A sixteen-element tunnel diode grid oscillator successfully operated at 2 GHz [6]. The series connection of tunnel diodes (Fig. 1(a)) in order to increase the oscillator output power was proposed and successfully demonstrated at low frequencies in 1965 by Vorontsov and Polyakov [7]. The series integration of RTD s by an MBE growth technique was proposed to enhance the output power of an RTD oscillator at millimeter- wave frequencies [8]. An example of a series integrated structure with three RTD's grown at UCLA is shown in Fig. 1(b) [9].

An oscillator with a series connection of tunneling diodes should generate significantly higher power than a single diode oscillator, however that is not the only difference between the two oscillators. In some configurations of the series connection, maximum oscillation frequency may be increased as well. 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.

Owing to this DC instability, a simple DC battery is not sufficient to bias all of the tunneling diodes simultaneously in the NDR region. Another consequence of this DC instability is that the diodes cannot stay simultaneously biased in the NDR region, unless there is an oscillation signal (or extemal RF signal) present in the circuit that satisfies the following requirements: the oscillation amplitude must be sufficiently large to cover a considerable ponion of the positive differential resistance (PDR) region of the DC I-V curve [7,8], and the oscillation frequency must be sufficiently high so that the time that the diode operating points spend in the NDR region during one oscillation period is small compared to the diode RC constant. A large signal design is required to assure that the oscillation amplitude will be above the minimum value.

In this paper, increase in power and high frequency cutoff is calculated for several configurations of the series connection. Biasing problem and

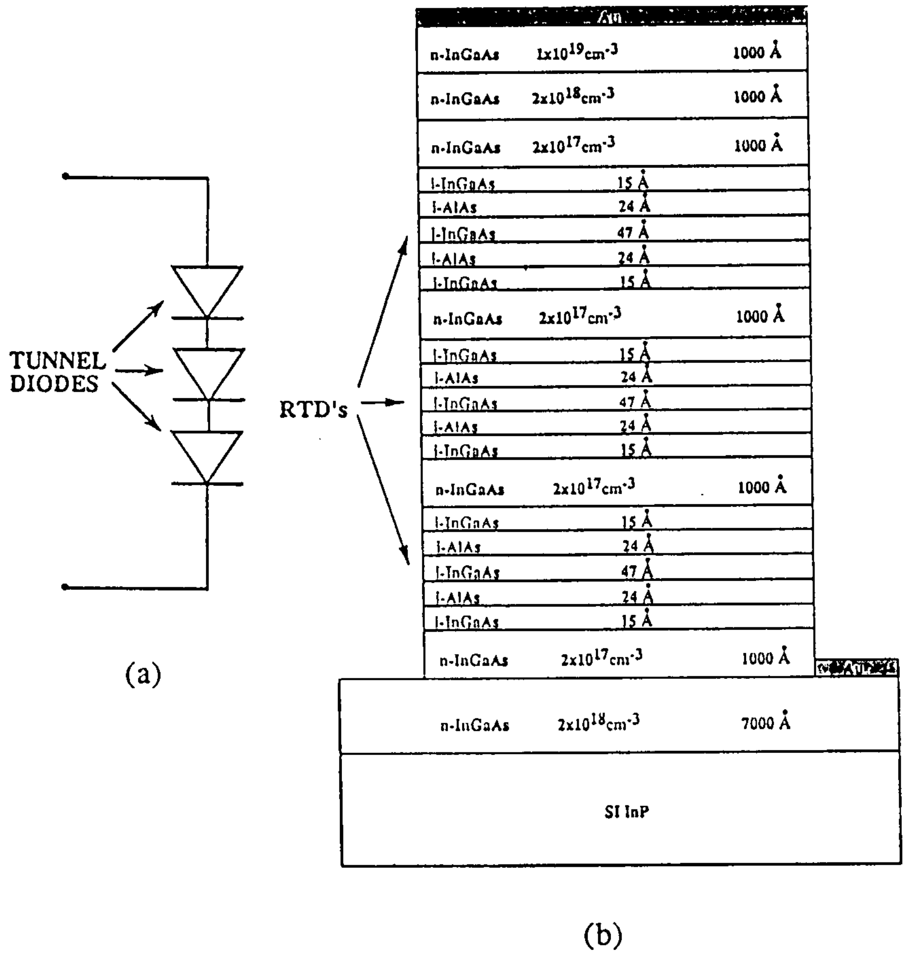

Fig. 1. Series connecdon of (a) tunnel diodes, and (b) a vertically series integrated device with three RTD's.

possible solutions are described. Large signal oscillator design is then briefly explained on an example of a series connection of commercially available tunnel diodes. Based on the large signal design, several oscillators with a series connection of tunnel diodes were fabricated and tested. RF triggering was successfully demonstrated experimentally. A brief summary of up-to-date obtained experimental results is presented.

2. Increase in power and high frequency cutoff for the series connection

A single RTD or a tunnel diode can be represented as a parallel connection of a capacitance C and a voltage contrnlled current source I(V), with a series resistance RS to account for ohmic losses of the device (Fig. 2), and a series inductance LS that comes from the bonding wire or whisker that makes the connection between the diode and the circuit. Alternatively, the voltage controlled current source I(V) may be represented as a differential conductance G. Both the capacitance C and the differential conductance G are a function of the applied DC bias and RF voltage, since both C-V and G-V curves are nonlinear (10). However, the variation in capacitance C is only 10-20%, much smaller than the variation in conductance G (10). Hence, for a given DC voltage, only conductance G will be considered a function of the RF voltage amplitude. The single diode impedance can be calculated as:

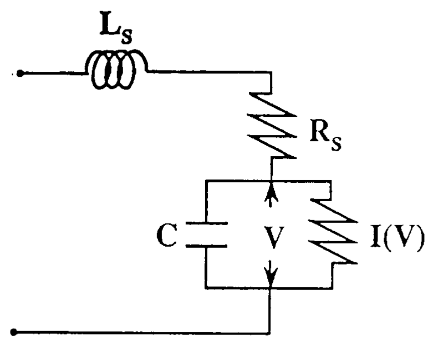

Fig. 2. Single diode equivalent model

$$\begin{aligned} Z_d =& R_s + R_d + jX_d \\ =& R_s + \frac{G}{G^2+(\omega C)^2} + j\omega\{L_s - \frac{C}{G^2+(\omega C)^2}\} \end{aligned} \tag{1}$$

Fig. 3 shows the typical shape of the DC I-V curve for a single tumel diode. If the diode bias voltage is between the peak voltage V_p and valley voltage V_v (NDR region in Fig. 3), the differential conductance G is negative.

The highest frequency at which the diode exhibits negative resistance can be found as

$$f_c(R_s + R_d = 0) = \frac{\mid G \mid}{2\pi c} \cdot \sqrt{\frac{1}{R_s \mid G \mid} - 1} \tag{2}$$

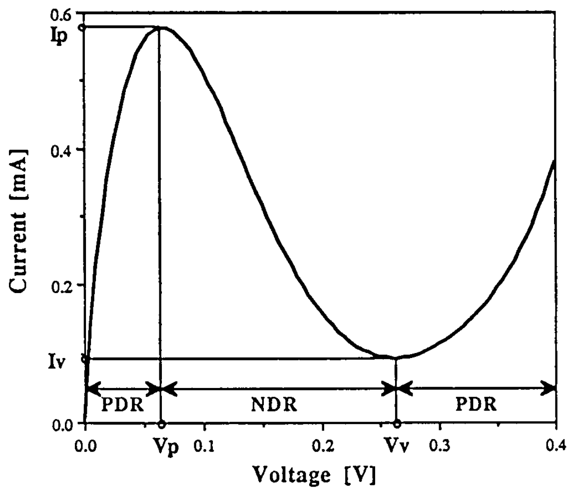

Fig. 3. Typical shape of the DC I-V curve for a single tunnel diode.

For a bias voltage in the NDR region and for all frequencies below the high frequency cutoff, f_c, the real part of the diode impedance is negative and therefore the diode can be used as an active device in an oscillator. The available power from the device can be calculated as:

$$P_{av} = \frac{1}{2} \mid G \mid V_{rf}^2 \tag{3}$$

where V_{rf} is the oscillation amplitude. Since G is a strong function of the oscillation amplitude $V_r f$, diode impedance Z_d, high frequency cutoff f_c, and available power P_{av}, will be a function of the oscillation amplitude as well. A simple oscillator model for one diode is shown in Fig. 4. The portion of the power available from the device that can be delivered to the load R_1 depends on the diode series resistance, and can be found as:

$$P_1 = \frac{P_{av}}{R_s + R_1} R_1 = \frac{\mid R_d - R_s \mid}{\mid R_d \mid} P_{av} \tag{4}$$

By connecting N diodes in series as shown in Fig. 1(a) [7], assuming that all diodes are identical and biased at the same voltage, the equivalent impedance of the series connection Z_{dn}, is simply the sum of individual diode impedances. Since peak and valey current through the series connection are limited by those of a single diode, RF current amplitude stays the same as for the single diode oscillator. However, the RF voltages of each diode will add if the diodes are oscillaung in phase, thus effectively multiplying the RF voltage amplitude by N times. Therefore, available power will be increased N times as well. Since both losses and the available power increase N times, power delivered to the load P_{ln} will also be increased N times. The high frequency cutoff will be the same as for a single diode (Eq. 2).

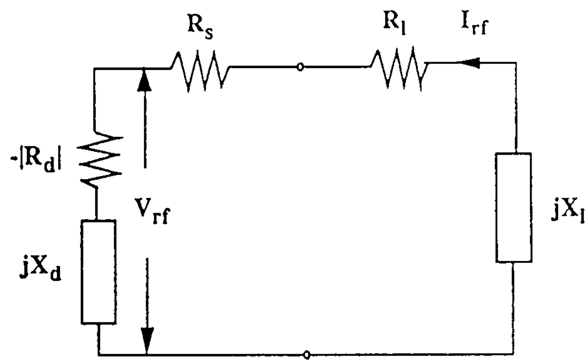

Fig. 4. Single diode oscillator model

In vertical series integration, several RTD's are grown one on top of another as a single device (Fig. 1(b)). Individual diodes are isolated by depletion layers. The area of the integrated device that consists of N diodes, A_n, may be kept the same or increased N times as compared to the single diode area A. If the series integrated device area A_n is kept the same as a single diode area A, the series resistance and inductance will stay the same as for a single diode whereas conductance G and capacitance C will decrease N times (Fig. 5(a)). Similarly, as for the simple series connecuon case, RF current swing stays the same, while the voltage swing will increase N times. Available power will be N times the available power of a single diode, but power delivered to the load P_{ln} will be higher than $N\ P_1$, since ohmic losses scale by less than N:

$$P_{ln} = \frac{N \mid R_d \mid - R_s}{N \mid R_d \mid} N P_{av}. \tag{5}$$

For the same reason, there will be an increase in the high frequency cutoff f_{cn} as compared to the single diode high frequency cutoff f_c (Eq. 4):

$$f_{cn} = \frac{\mid G \mid}{2\pi C}\sqrt{\frac{N}{R_s \mid G \mid} - 1}. \tag{6}$$

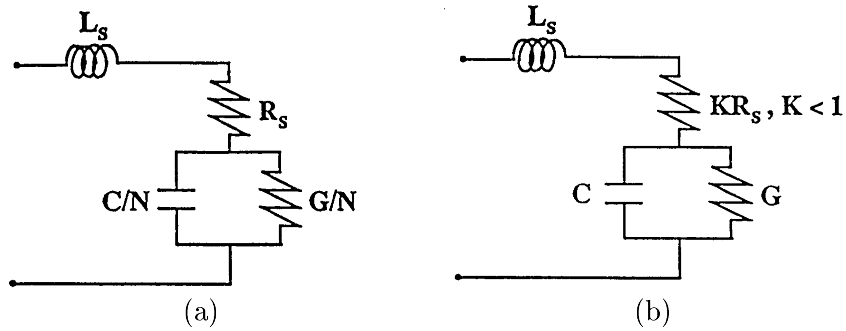

Fig. 5. Equivalent impedance of a vertical series integrated device if (a) $A_n = A$, and (b) $A_n = NA$.

If the series integrated device area A_n is increased N times as compared to the single diode area A, the equivalent capacitance C and conductance G will be the same as for a single diode, parasitic inductance L_s will stay the same, whereas series resistance R_s will decrease (Fig. 5(b)). Since only the contact resistance component of the series resistance decreases proportionally to the increase in area, R_s will decrease less than N times. In this case, both RF voltage and current amplitude may be increased N times, and therefore available power may be increased N^2 times. Due to the decrease in R_s power delivered to the load will be higher than N^2 times P_1:

$$P_{ln} = \frac{\mid R_d - KR_s \mid}{\mid R_D \mid} N^2 P_{av}, \quad K < 1, \tag{7}$$

where K is a measure of a decrease of R_s. The high frequency cutoff f_{cn} will be slightly increased as compared to f_c:

$$f_{cn} = \frac{\mid G \mid}{2\pi C}\sqrt{\frac{1}{KR_s \mid G \mid} - 1}. \tag{8}$$

In this case the same oscillator circuit used for the single diode may be used for the integrated device, since the total device impedance is almost unchanged.

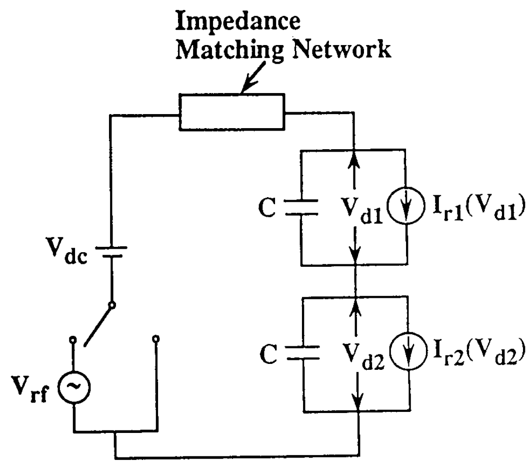

Fig. 6. Simplifed model of a circuit with two tunneling diodes connected in series

3. Biasing problem and possible solutions

Due to the 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. Also, it is very difficult to bias tunneling diodes in the NDR region at the same rime. As an example, we can assume that there are two tunneling diodes connected in series and biased with one DC battery (Fig. 6). As the bias voltage is incrcased slowly from 0 to $2V$, both diodes will be biased on the first rising branch, and bias voltage will be equally divided between the diodes. If the bias voltage is further increased, the diode bias points will cross to the NDR region. 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 [7]. Effectively, bias voltage would be increasing on one diode, and decreasing on the other diode. 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 (R_n is the slope of the I-V curve in the NDR region), the diode bias points will switch to the PDR region. Therefore, a DC battery cannot be used to bias several tunneling diodes simultaneously in the NDR 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 so that all the diodes are biased in the PDR regions, some on the first and others on the second rising branch. The DC I-V curve of the series connection exhibits multiple peaks, because the diodes cannot simultaneously be biased in the NDR region. Fig. 7 show the DC I-V curve of three vertically integrated RTD's for a $50 \mu m$ diameter device, measured using an HP 4145 curve tracer. Because of the high series resistance, NDR regions are very small, which made it very difficult to use this device in an oscillator.

The biasing problem is the main disadvantage of an oscillator with several tunneling diodes connected in series. However, there are several effective solutions to this problem: fast electric pulse excitation, RF excitation, optical illumination and successive triggering.

Fast electric pulse excitation was originally proposed by Vorontsov and Polyakov [7], as a fast switch for a DC bias. Yang and Pan proposcd using a nonlinear transmission line (NTL) to gencratc a fast voltage pulse required for excitation [8]. However an NTL would trigger the oscillator periodically resulting in a pulsed, rather than a CW output signal. Alternatively, a very fast switch, such as PIN diode or perhaps an RTD, could be to turn on the DC bias. If the DC bias voltage has a fast turn-on time, so that the rate of increase of bias voltage is highcr than the rate of increase of the difference in individual bias voltages ΔV_d, the diodes may be biased simultaneously in the middle of the NDR region. The necessary turn-on time for the bias voltage can be estimated based on the difference in peak current ΔI_p on individual devices [7]. However, for small ΔI_p as is expected for vertical series integration, other factors will be more relevant, such as diode RC constant and oscillation build-up time [11]. During the DC bias rise time and oscillation build-up time, ΔV_d should not become comparable to the extent of the NDR region, for successful biasing.

More recently, RF triggering was proposed as a much more practieal solution to the biasing problem [12]. RF triggering is very easy to implement experimentally, requires little power, and signal of frequencies much lower than the frequency of oscillation can be used for triggering. Initially DC voltage suffcient to bias all diodes in the middle of the NDR region is applied, and the DC instability distributes it so that all diodes are biased in the PDR region, and all diodes draw the same current. When an external RF signal

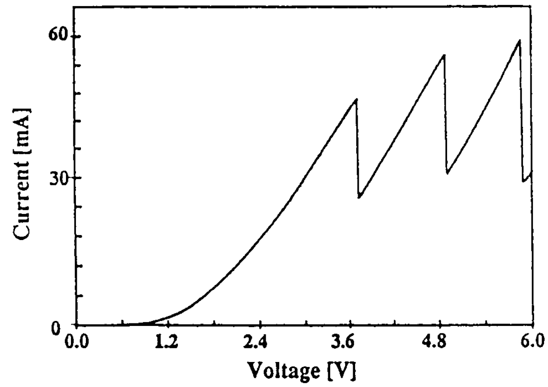

Fig. 7. DC I-V curve for three vertically integrated RTD's.

is applied, the DC components of conductive currents will change due to the high nonlinearity of the DC I-V curve of the tunneling diode. This change in current will trigger the motion of the bias points towards the NDR region, and if the applied RF signal is strong enough, bias points will switch from the PDR to the NDR region. The RF signal may be applied through a circulator, power divider, or spatially. The RF excitation frequency can be chosen close to the oscillation frequency (fundamental excitation), or much lower (subfrequency excitation). Once initiated, output signal is completely independent of the frequency and power of the excitation signal.

Optical illumination as another way of solving biasing problem was proposed in [13]. If an RTD is illuminated with light of an appropriate wavelength, enough carriers may be generated to produce high enough current to quench the NDR region. Once the NDR region is quenched, there is no DC instability, and the DC bias voltage can be equally distributed among the diodes. If the recombination time is fast enough and the oscillator circuit is well designed, when the light is turned off oscillation will occur. Preliminary experiments have shown that the NDR region becomes smaller under illumination [13]. It has later been experimentally demonstrated that the NDR region may be eompletely quenched under illumination [9].

Successive triggering may happen in circuits with smaller number of diodes [7], designed for a very large oscillation amplitude. Unfortunately, it is not a systematic solution to the biasing problem, since an oscillator design to achieve successive triggering would be very complex. If the DC bias voltage is applied gradually to the series connecaon, one diode will eventually become biased in the NDR region. If the oscillation condition is satisfied in a broad impedance range, the diode biased in the NDR region may start oscillating. As bias is further increased, the oscillation may be sustained while each diode bias point is gradually brought into the NDR region. This can happen only if the oscillation condition is satisfied for all successive cases: one diode active and the others acdng as passive loads, two diodes active and the others acting as passive loads, and so on.

4. Large signal oscillator design

Accurate characterization of the large signal device impedance is very important for the successful design of any nonlinear circuit. In the case of an oscillator, knowledge of the large signal impedance of the active device is important to maximize the oscillator output power. For a single tunneling diode oscillator, due to a broad range of values of negative resistance and the absence of a low frequency cutoff, an osciilation 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. For such an oscillator there is a minimum oscillation amplitude below which oscillation cannot be maintained [7], [8]. Therefore, it is critical to provide the impedance match between the oscillator circuit and the device at the desired oscillation amplitude level.

A simple nonlinear analysis based only on the diode DC I-V curve was described in [14]. This method is essentially a simplified harmonic balance method. Negative conductance, available power, high frequency cutoff and other parameters were calculated as a function of the oscillation amplitude. All calculations were done using The Math Works Inc. MATLAB program [15].

A low peak current tunnel diode (back diode) M1X1168 manufactured by Metelics Co. was analyzed, having a peak current of $0.55mA$, a junction capacitance of $0.32pF$, a series resistance of 6.5Ω, and a package capacitance of $0.23pF$ (diode I-V curve in Fig. 3). Calculations were done for several DC bias voltages in the NDR region, and it was found that maximum power occurs for a bias voltage closer to the valley than to the peak of the DC I-V curve. Similar findings were presented in (16). The oscillation amplitude at which maximum power is generated determines the diode impedance for the optimum circuit design. It is possible that poor impedance matching was responsible for the very low output power and DC-to-RF conversion efficiency of some RTD and tunnel diode oscillators reported in the literature [5].

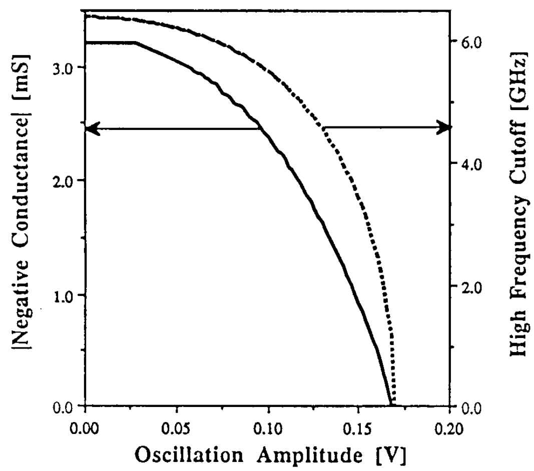

Fig. 8. Negative conductance and high frequency cutoff versus oscillation amplitude for a low power tunnel diode

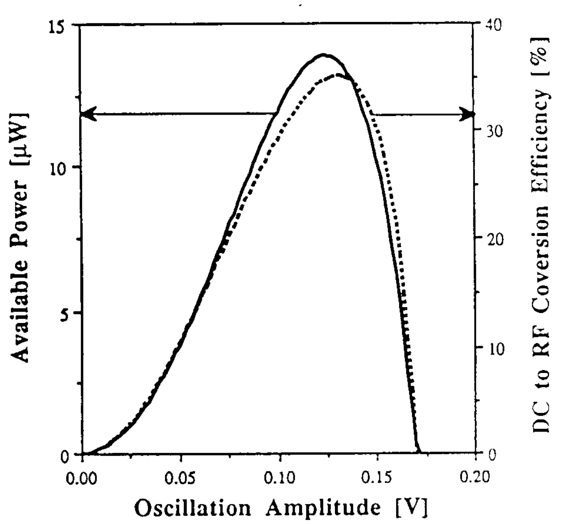

Fig. 9. Available power and efficiency versus oscillation amplitude for a low peak current tunnel diode

Fig. 8 shows the negative differential conductance and the high frequency cutoff, and Fig. 9 the available power and DC-to-RF conversion efficiency (ohmic losses not included) as a function of the oscillation amplitude and for a DC bias voltage in the middle of the NDR region ($0.155V$). 6 Oscillation amplitude was chosen to be above the minimum value determined in [17), and diode impedance was calculated accordingly. The oscillator design frequency was chosen to be 2 GHz and 2.5 GHz to assure that oscillation will occur for an amplitude as large as $0.17V$. The impedance of the senes connection was found taking into account phase delay between diodes due to the package [18]. Oscillator impedance matching circuit was designed in microstrip configuration using HP-EEsofs Touchstone program (19).

5. Experimental results

RF triggering was demonstrated experimentally for oscillators with a series connection of tunnel diodes (described in Section 4) at microwave frequencies. Brief review of most important experimental results will be given here.

Fundamental excitation was examined in detail for one-port oscillators with two tunnel diodes in series at 2 GHz [20]. It was found that the required excitation power is more than $10dB$ lower than the output power. Therefore a low power source such as a single RTD oscillator may be used as an external RF source. Since excitation is applied only for a couple of seconds, a device that has a heating problem, such as pulsed IMPATT diode, may also be used for the excitation. Two-diode oscillators gave up to 2 dB higher power than one-diode oscillators. Spurious oscillations were not observed in any circuits.

Subfrequency excitation does not require much more power than fundamental excitauon, provided that the excitation frequency is one-half or one-third of the oscillation frequency. It was shown that there is no lower limit on the excitation frequency [21], however at very low frequencies larger power is required and excitation is not 100% repeatable. Subharmonic excitation may be a very useful way to initiate the oscillation at high frequencies, where signal sources are not readily available.

Fundamental excitation was also tested in active antenna configuration at 2.5 GHz. In this case, the RF triggering signal illuminates the antenna from a pyramidal hom, which then delivers it to the diodes. The quasi-optical approach does not require a circulator, since the RF source may be physically disconnected from the horn antenna, and the spectrum analyzer connected in its place, without disturbing the oscillation. At millimeter-wave frequencies, quasi-optical RF excitation would be a very useful technique since circulators are not readily available, and it would also be advantageous for applications involving spatial power-combining arrays.

6. Conclusions

Connecting several tunneling diodes in series was shown to be a feasible method for increasing the output power of oscillator circuits using these devices. Increase in power and high frequency cutoff was calculated for several configurations of the series connection The biasing problem and special methods of biasing the series connection were discussed. Large circuit oscillator decsion was explained on an example of a senes conncction of commercially available tunnel diodes. Thc biasing problem was successfully solved using an external RF source to trigger the oscillation. RF triggering was demonstrated in proof-of-principle experiments at microwave frequencies, for oscillators with several tunnel diodes connected in series.

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