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Computer-Aided Design and Experimental Applications of Tunnel Diodes As A Narrow Band Amplifier Systems

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ABSTRACT. The purpose of this paper is to shed further light on the operating characteristics and limitations of tunnel diode amplifier circuits, particularly those with different doping concentrations. This has been achieved by a theoretical modeling, economical computer programs and experimental measurements. The behaviour of the tunnel diode operating at high frequency circuits, and the effects of material parameters and doping levels on their performance are presented and discussed. This leads to a better understanding of these devices and their limitations. It is found that the amplifier gain exceeds unity, and it increases with frequency reaching a peak at a certain value of the operating frequency,then it decreases at higher frequencies, down to a constant plateau. Results of the predicted, measured gain show that it depends on the device physical parameters and its material, circuit parameters, and operating conditions. The shape of the response curve of the amplifier circuit is a function of the dynamic negative conductance and also the resonance nature of the circuit.

The tunnel diode invented by "Leo Esaki" in 1958 (Esaki 1976), is a device that can function efficiently either as an amplifier or an oscillator. It is a pn-junction in which both the n-and p-regions are heavy doping conditions, the contact potential is large, the space-charge region is very narrow and the field in this region is extremely high.

A number of researchers have investigated the characteristics of such negative differential resistance devices. The aim of this work is to suggest a computer program to solve the general equations for the devices and to introduce the effect of device physical parameters, circuit terms as well as, operating conditions upon their performance as a high frequency amplifier, as well as, to compare the calculated results with those obtained experimentally. The suggested computer program permits easily the user to select operating conditions and calculate the effect of various device parameters on the investigated amplifier circuit. Calculations of the effective value of the gain of tunnel diode amplifier circuit, and the phase angle (φ) using different tunnel diode physical-and circuit-parameters as well as operating conditions are shown in Appendix.

Static Parameters of Tunnel Diode:

Tunnel diodes belong to the devices exhibiting a negative differential resistance which enables the tunnel diodes (Stupelman and Filaretov 1976) to amplify and generate signals. The tunneling current is proportional to the number of overlapping energy levels in the valence band and in the conduction band of the p-and n-type materials. In the forward biased junction, the fermi level becomes so shifted that opposite the vacant levels in the valence band of the p-region there develop filled levels in the conduction band of the n-region with the result that the tunneling current of electrons flows across the pn-junction from the n-region to the p-region. This current will continue increasing to its highest value until the overlapping reaches a maximum. The maximum overlap sets in, when the forward voltage

$$V_p = (E_{fn} + E_{fp}) \ / \ 3 \ q \quad \text{.........................(1)}$$

As the voltage is further increased, the number of overlapping levels decreases and at the voltage

$$V_v = (E_{fp} + E_{fn}) \ / \ q \quad \text{.........................(2)}$$

this number goes to zero and the current flowing through the diode reduces,now,to a minimum. At voltages above (V_v) the usual forward diffusion current passes through the pn-junction, which continues to grow with increasing voltages (Fig.1).

The parameters of the tunnel diode are now; peak voltage (V_p); peak current (I_p); valley voltage (V_v); valley current (I_v) and the voltage (V_{fp}) at which the diffusion current is equal to the peak current. Voltages (V_p) and (V_v) depend on the values of (E_{fp}) and (F_{fn}). *i.e.*, on the degree of doping of the p-and n-region of a semiconductor (Gerasimov *et al.* 1980). Valley current, also called excess current, depends on the density of levels in a semiconductor band gap, which are responsible for the presence of the tunneling current at voltages higher than (V_v). The larger the number of energy levels in the band gap, the higher the valley current. On the other hand, voltage (V_{fp}) depends on the width of a semiconductor band gap.

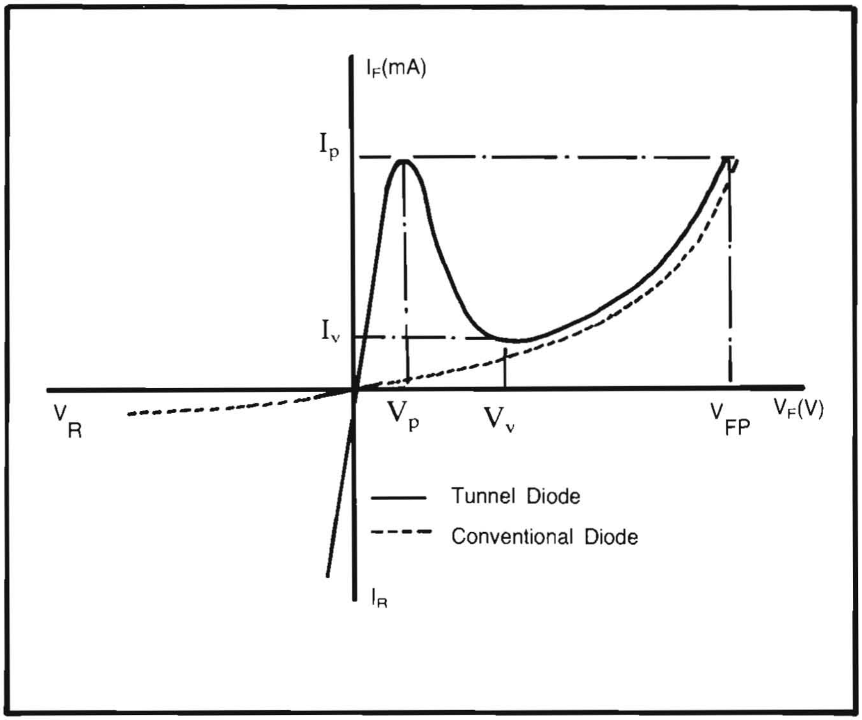

Fig. 1. (Volt - Ampere) Curve for Tunnel Diode.

A major property exhibited by the tunnel diode, allowing it to operate as an active element of the circuit, is a differential negative resistance which develops at voltage $V > V_p$. Its value is determined from the empirical formula:

$$-R_o \text{ (ohm)} = 200/I_p$$
$$\text{(for GaAs-diodes)} \quad (3)$$

and the diode will function as an amplifier when the condition $|R_o^-| > |R_L|$ is satisfied, otherwise the stability of the tunnel diode negative resistance will become dependent on the external resistance. The parameters of some of the investigated Soviet-made tunnel diodes are presented in Table (1).

Tunnel Diode Dynamic Parameters:

Two dynamic parameters (Gerasimov *et al.* 1980, Bruk *et al.* 1969 and Streetman 1980) which are useful in the selection of tunnel diodes for different applications are the resistive cut-off frequency (F_c) and the self resonant frequency (F_r). Their values are given when the total series impedance of the tunnel diode equivalent circuit is considered. The input impedance of the equivalent circuit of the tunnel diode, at high frequency(Bruk *et al.* 1069) across the terminals «a», «b» is as shown in Fig. (2).

$$Z = R_s - \frac{R_o}{1 + (wC_D\ R_o)^2} + Jw\left(L_s - \frac{C_D}{(1/R_o)^2 + (wC_D)^2}\right) \quad \ldots\ldots\ldots\ldots\ldots (4)$$

where:

R_s: Total series resistance (bulk resistance of the diode plus any contribution due to the ohmic contact of the leads).

L_s: Self inductance of leads, which is effective at high frequencies. It depends upon the lead length and the geometry of the diode package.

C_D: Diffusion capacitance at the junction of a forward-biased diode. Its value is directly proportional to the diode width and the applied bias voltage.

The cut-off frequency is the frequency above which the real part of the diode impedance is positive. Equating the real part of Equ. 4 to zero, the cut-off frequency is obtained (Stupelman and Filaretov 1976).

$$F_c = \frac{1}{2\pi\ C_D\ R_o} \sqrt{\frac{R_o}{R_z} - 1} \quad (5)$$

Table 1. Electrical Characteristics of GaAs Tunnel Diodes.

Particulars	Diode Types			
	3И 301A	**3И 301 σ**	**3И 301B**	**3И 301r**
Peak current, Ip. mA at + 25 °C	2	5	5	10
Minimum I_p/I_v	8	8	8	8
Maximum V_p, Volt	0.18	0.18	0.18	0.18
V_{fp}, Volt	min. 0.65	0.85-1.15	1.0-1.30	min. 0.8
C_D (Max. Total), pF	12	25	25	50

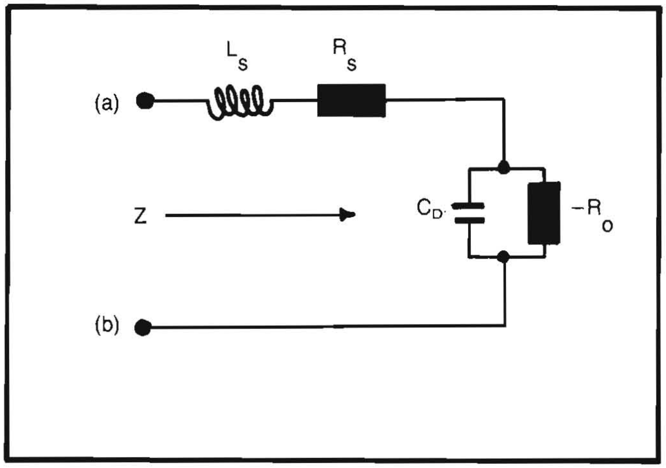

Fig. 2. High - Frequency Equivalent Circuit of Tunnel Diode.

On the other hand, self-resonant frequency (F_r) of the tunnel diode is the frequency of resonance of the inductive reactance and the capacitive reactance and is given by equating the imaginary part of Equ. 4 to zero, then:

$$F_r = \frac{1}{2\pi\ C_D\ R_o} \sqrt{\frac{C_D\ R_o^2}{L_S} - 1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (6)$$

The effective negative resistance (R_o) displayed by a given tunnel diode in a circuit depends on the operating frequency (F_o). Its value calculated from the (I-V) characteristics by using incremental dc-values, does not consider the shunting effect of the inherent capacitane (C_D) of the diode. The following equation permits calculation of the effective negative resistance at any particular operating frequency(Stupelman and Filaretov 1976).

$$R_o^- = R_o\ /\ (\ 1\ +\ (\ 2\ \pi\ F\ C_D\ R_o\ )^2) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

Experimental Procedures:

1. Dc-Characteristics

Seven different types of «GaAs» and «InSb» tunnel diodes namely: 3И301B, АИ301r, Au301A, A 301Г, АИ301σ, АИ301 A and YГ were subjected to several tests in order to plot their output characteristics. Tektronics 577-177-D1 storage curve tracer, which is a dynamic component tester was used in plotting the (I-V) curves of the investigated samples. From these: peak voltage and current, valley voltage and current, forward peak voltage and the effective negative resistance can be obtained.

2. Amplifier Circuit Analysis

The tunnel diode (Chirlian 1960, Virk 1987) can often be used as the active element in a conventional amplifier circuit. Since the tunnel diode is a two-terminal device it does not supply the isolation of either the vacuum tube or the transistor. Thus special techniques must be used when cascading tunnel-diode amplifiers. For convenience, voltage amplification will be discussed although a similar discussion could be applied to current-or power-amplificition.

In order to determine the voltage gain of the circuit amplifier using different tunnel diode types, the simple circuit shown in Fig. (3) is presented. The circuit contains two inductive coils (L_1,L_2) connected in such a way to form "π-section" filter, a capacitor C_c, and the tunnel diode. The elements L_1, L_2 and C_c are used to supply direct-bias, while R_L is the load resistance. The experimental values of the circuit parameters were chosen according to theoretical calculations for obtaining the optimum conditions of the voltage gain of the circuit amplifier. They are: $L_1 = L_2 = L_C = 25\ \mu H$, $C_C = 1000$ pF, and $R_L = 10$ k.ohm.

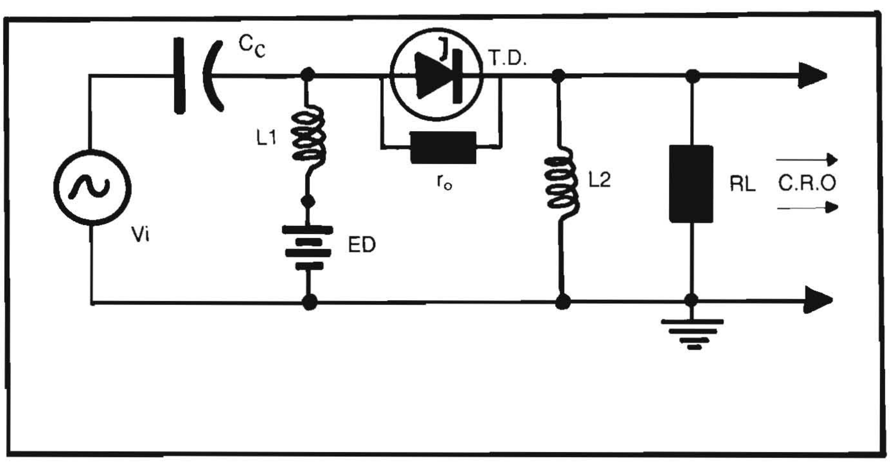

Fig. 3. A Simple Tunnel-Diode Amplifier.

Results and Discussion

In order to investigate the factors that affect the gain of the tunnel diode amplifier, six types of GaAs diodes namely: 3 И 301 B, A И 301 r, Au 301 A, A И 301 Г, A И 301 σ and 3 И 301 A were subjected to such study. Besides, device material effects was also considered applying InSb, tunnel diode type Y Г.

DC-Characteristics

Fig. (4) illustrates the (I-V) characteristics of two different tunnel diodes. Interesting feature of the two curves is the presence of a NDC (Negative - Differential Conductivity) region in which an increase in the voltage actually leads to a decrease in the current. This NDC device can be used either as amplifier or oscillator in a wide spectrum of electronic systems. The physical basis (Omar 1975) for amplification is due to that, when a signal is applied to a circuit element of a «NDC» character, the current produced is opposite to the field. hence energy absorbed from the element and the signal field, is amplified.

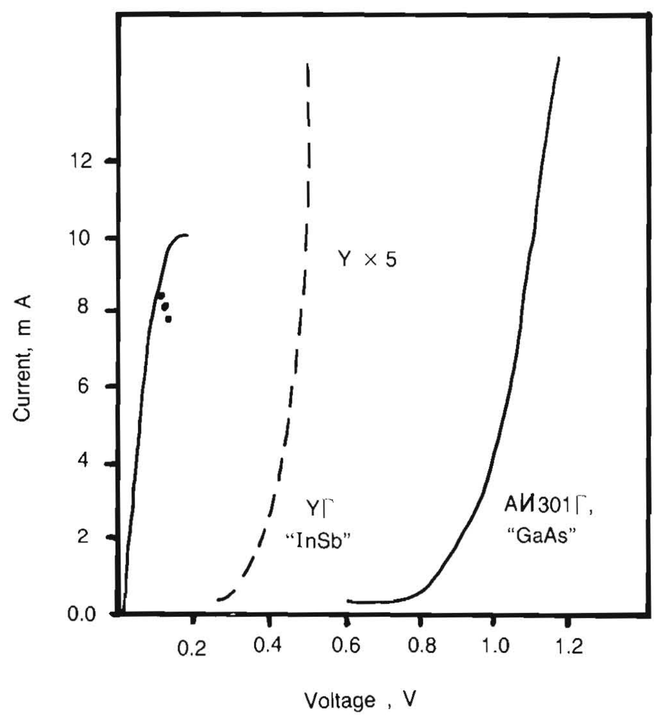

Fig. 4. Characteristics for two Different Tunnel Diode Types.

Response Characteristics

The dependence of the gain on the frequency was plotted at an input signal amplitude of 20 mV in the frequencies range from 1 to 10 MHz. Moreover, the amplitude characteristics were measured at the frequency of the peak gain. Fig. (5) shows the variations of the amplifier gain (A) with the frequency of the input signal (F) for the Au301A GaAs sample. It is clear that the gain of the amplifier increases as a function of the input frequency, reaching a peak value, then decreases at higher frequencies (narrow band amplifier). Fig. 6 shows the amplitude characteristics for the tunnel diode amplifier at the frequency of the peak gain, where a linear ralationship between input and output signals, with a correlation coefficient of 0.99975, was achieved. Plate (1) shows the input-and output-signal for GaAs tunnel diode amplifier circuit.

Effect of Device Parameters

Both the theoretical and experimental results of the dependence of the amplifier gain on the device parameters are shown to be in close agreement. Table (2) illustrates the obtained results for the whole investigated samples. The gain of the tunnel diode amplifier was shown to increase as a function of its negative- and minimum negative-resistance (R_m) values, the extracted power level, peak current, the currents ratio, valley voltage, and forward peak voltage. On the other hand, the increase in the device valley current value, the V_v/V_p ratio and voltage swing are shown to cause pronounced decrease in the gain value. Such results are in good agreement with the theoretical expectations mentioned earlier.

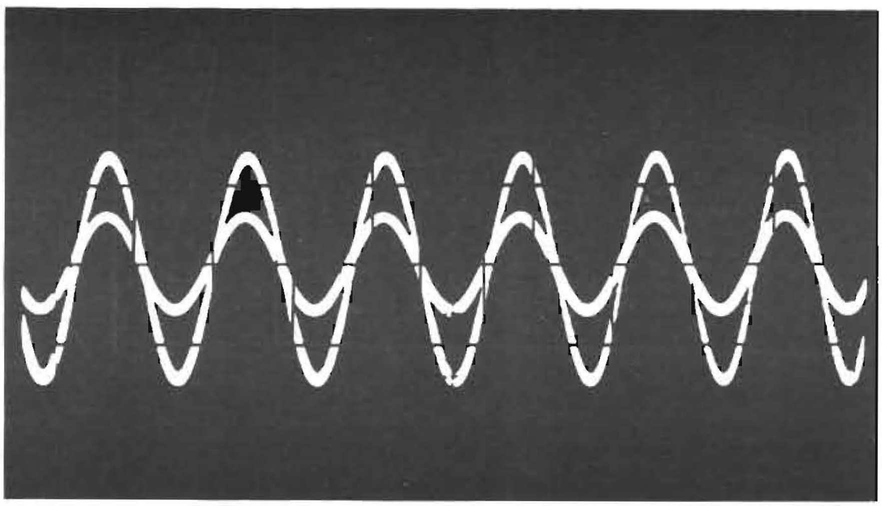

Plate 1. Input-and Output-Signals for «GaAs» Tunnel Diode Amplifier Circuit. (U_o = 043 V, F_o = 2 3 MHZ, V_I = 20 mV)

Table 2. Dependence of the Gain on Device Parameters

Parameter	Direct	Inverse	Correlation
Vv/VP	.....	X	−0.60
Iv	.....	X	−0.51
Voltage Swing	.....	X	−0.60
Ip/Iv	X	.....	+0.93
Power	X	.....	+0.60
Ip	X	.....	+0.65
−Ro	X	.....	+0.50
Vp	X	.....	+0.74
Rm	X	.....	+0.73

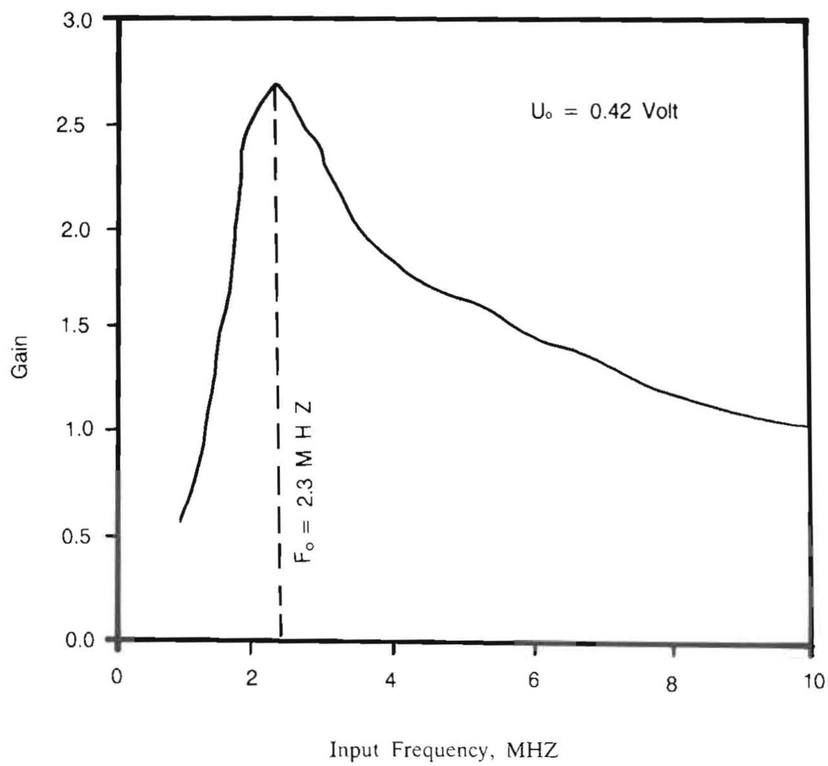

Fig. 5. Gain-Frequency Dependence for the Amplifier Circuit Using Tunnel Diode of the Type Au 301 A.

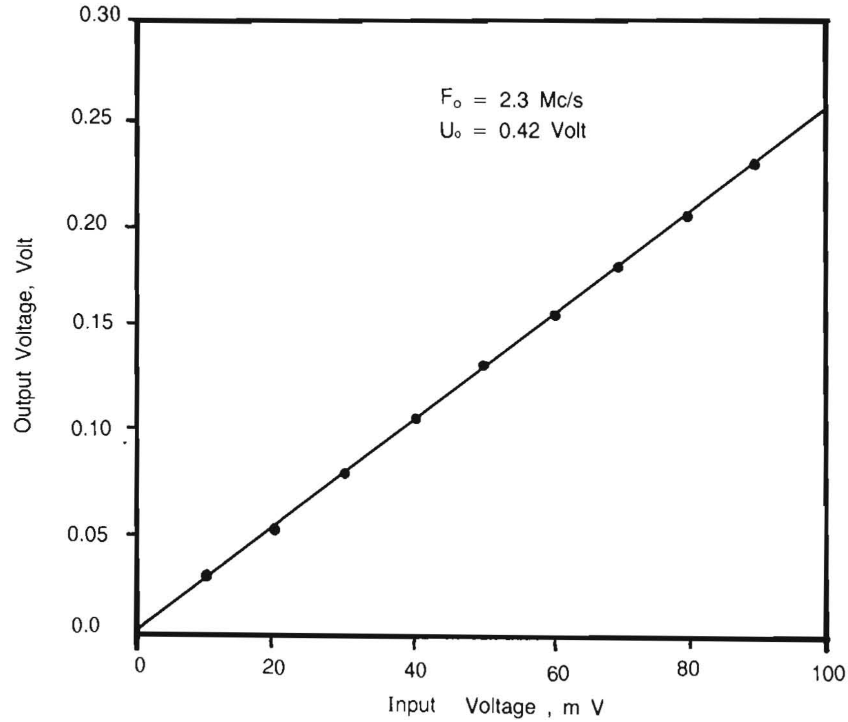

Fig. 6. Amplitude Characteristics for the Amplifier Circuit at the Frequency of the Peak Gain.

Effect of Device Material

The effect of the devices material on the amplifier response characteristics were obtained theoretically and experimentally for both the diode types Au301 A (GaAs) and YГ (InSb), where the obtained results are plotted in Fig's. (7 and 8) and summarized in Table (3). The peak gain point of the two devices occur at different frequencies. Also, the gain was shown to be with different amplitudes. The gain obtained for GaAs samples shows higher value than that value, either measured or calculated, for InSb samples. For all the tested samples, the peak gain for GaAs devices occur at higher frequency values.The variations in the gain amplitude of devices with different material types is attributed to the variation in the peak current value, which is a function of the impurity concentration and the junction area, energy gap and electrical parameters.

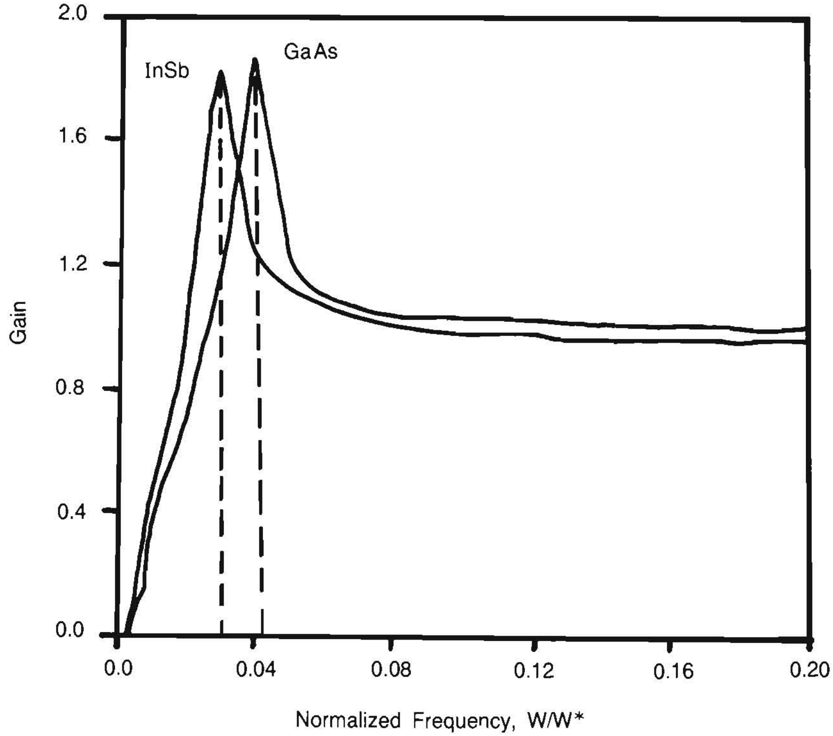

Fig. 7. Theoretical Results Showing the Effect of the Varying Devices Material on the Gain of the Amplifier.

Table 3. List of Diodes, Physical and Electrical- Characteristics as a Function of their Material.

Device	Material	Gain	− Ro	Rm	R_{Rev}	E_g,eV	μ_n	μ_p
AИ301 r	GaAs	2.95	19.60	0.029	120	1.340	0.851	0.045
YΓ	InSb	2.45	112.3	0.185	135	0.180	8.000	0.070

Effect of Circuit Parameters

a − L_c and C_c

Theoretical and experimental investigations were carried out in order to analyze the effect of the circuit parameters on tunnel diode amplifier characteristics. The

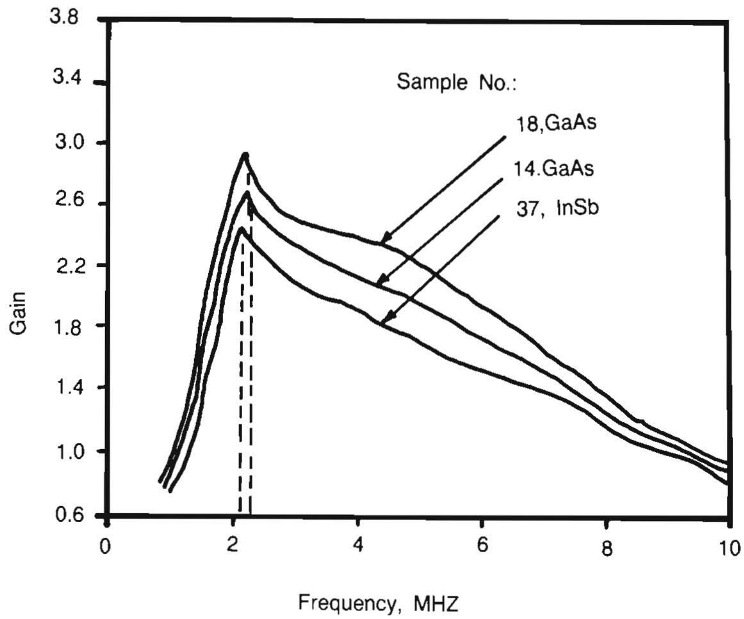

Fig. 8. Experimental Results Showing the Effect of the Devices Material on the Gain of the Amplifier Circuit.

values of the circuit capacitor (C_c) and inductor (L_c) were chosen to get the maximum gain (Chirlian 1961, Harbourt 1961, Moody 1961). They were calculated at the operating input frequency of 1 MHz. Fig. (9) shows the effect of varying the values of the circuit parameters (L_c) and (C_c) on the calculated gain at different normalized frequency values. It is clear from the figure that the gain is higher (3.4) as (L_c) takes the value of 125 μH, and C_c is 200 pF. On the other hand, the gain is lower as $L_c = 2.5$ μH and $C_c = 10000$ pF. Although the product of (L_c) and (C_c) is constant (25×10^{-15}) for all cases, yet the value of the gain,higher or lower, depends on the chosen values of circuit elements (L_c) and (C_c). Also, the shape of the calculated gain was shown to be function of both (L_c) and (C_c) values. The gain has sharp peaks for (L_c) values greater than 50 μH but less than 250 μH. On the other hand, the capacitor (C_c) has values greater than 100 pF and less than 500 pF. They were so that, because of their impedances. The gain has no peaks for (L_c) less than 5 μH and (C_c) higher than 5000 pF.

The experimental circuit parameters were chosen to have the values of $L_c = 25$ μH, $C_c = 1000$ pF, they were calculated at the operating frequency of 1.0 MHz. The resulted gain was shown to be with a value of "1.22" which is in close agreement with that theoretically calculated.

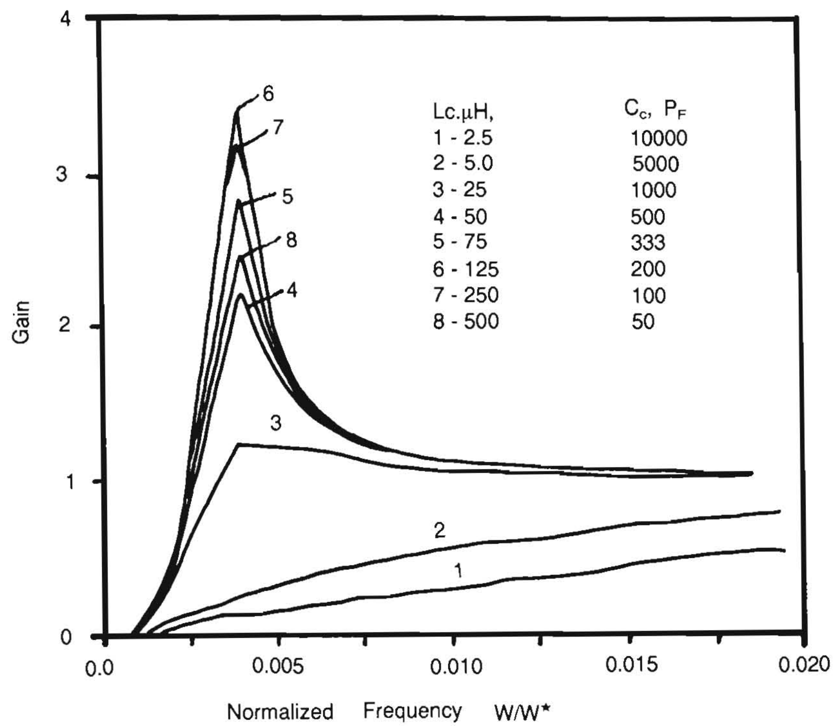

Fig. 9. Effect of Circuit Parameters (L_c,C_c) on the Calculated Gain of Tunnel Amplifier Circuit.

b). Load Resistance

The theoretical calculations for the optimum condition of the maximum gain of circuit amplifier using tunnel diode of the type 3 И 301B shows that the gain has greater value as the load has the value of 10 k.ohm. The gain is greater than unity, and less than this value, as (R_L) less than 10 k.ohm (Fig. 10).

Effect of Shunt Resistor

As pointed by Chirlian(1960), a stable amplifier can be obtained if the tunnel diode in the circuit is shunted by a small enough resistance. Let us presume that it was originally unstable, this shunting would shift the poles from the right half of the complex plane into the left half plane. Thus, for appropriate values of the shunting resistances, all the poles will lie in the left half plane and one pair of poles can be as close to the (Jw) axis as desired. This produces any desired gain at a given frequencies. In addition, the pole location is not the only factor that affects the gain. The zero location and the constant multiplier must also be considered.

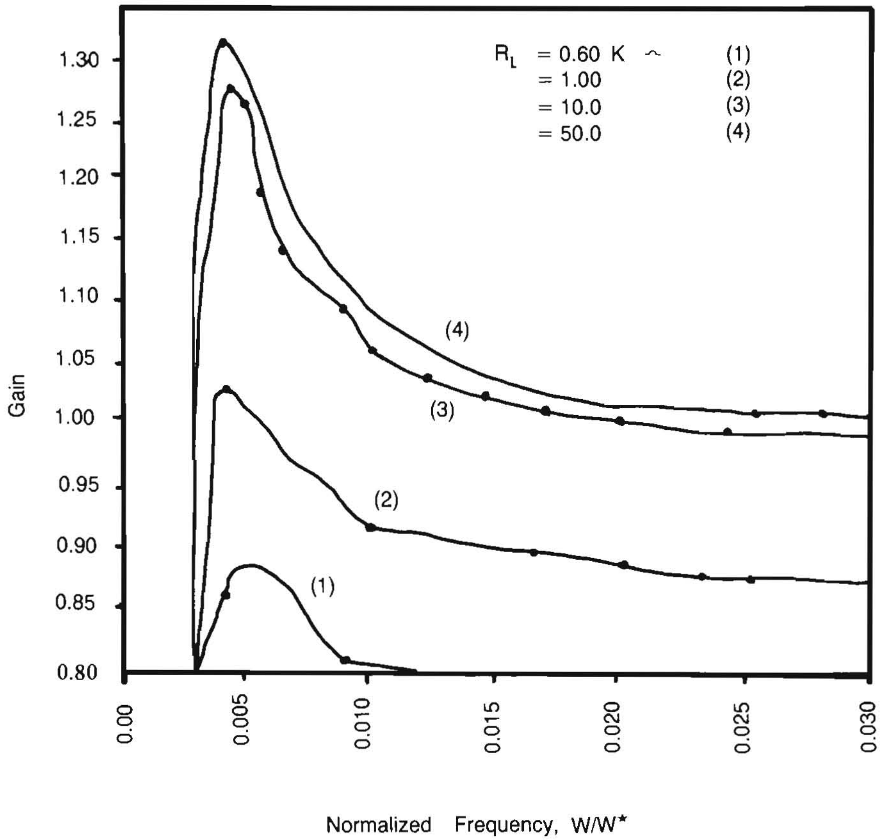

Fig. 10. Dependence of the Calculated Gain on the Normalized Frequency (n = W/W*) for Different Load Resistor Values.

The magnitude of the appropriate shunt resistance (r_o) values are computed to get the maximum gain for the amplifier circuit using tunnel diode of the type 3И301B. The theoretical shunt resistance values,adapted to calculations of gain,appear to be in general agreement with those realized in practice. Fig. (11) shows the effect of the shunt resistance values on the calculated gain of the circuit amplifier, where resistance values range from 0.1 ohm up to 10 ohm were investigated.It is clear from the figure that as the shunt resistor (r_o) be small enough, less than 1 ohm, the gain will be high.

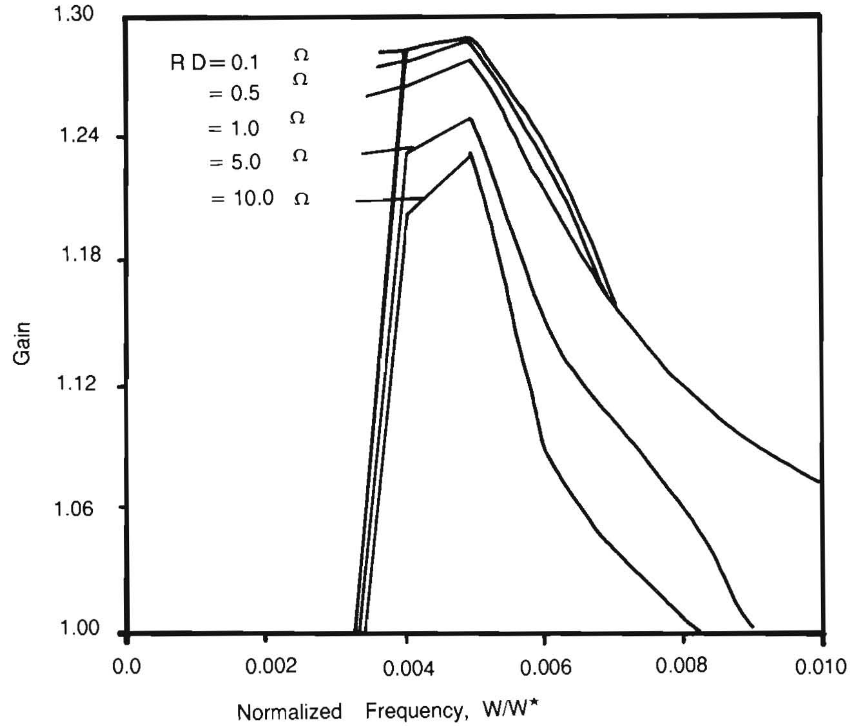

Fig. 11. Effect of Shunt Resistor on the Calculated Gain of the Circuit Amplifier.

Dependence of gain on Operating Conditions

1 - Dependence on Input Frequency:

The effect of the operating input frequency (F) on the theoretically calculated gain (A) versus the normalized frequnecy (N = w/w*) was studied for GaAs tunnel diode amplifier circuit. The study included, as shown in Fig. 12, three values of input frequencies: 10^7, 10^8 and 10^9 Hz, which corresponding to the: medium (short waves), high, and very high frequency ranges respectively. It is clear that the gain has a nearly constant value which ranges from "1.26" at F: 10^7 Hz to "1.29" at F: 10^9 Hz. On the other hand, the peak points are shown to be shifted toward lower normalized frequency values as the operating input frequency increases. The shape indicates function of the dynamic negative resistance ($-R_o$), the frequency and the resonance nature of the circuit (L_c and C_c). The theoretical calculations of the gain as a function of the operating frequency are shown to be in good agreement with those results obtained experimentally at the same operating conditions.

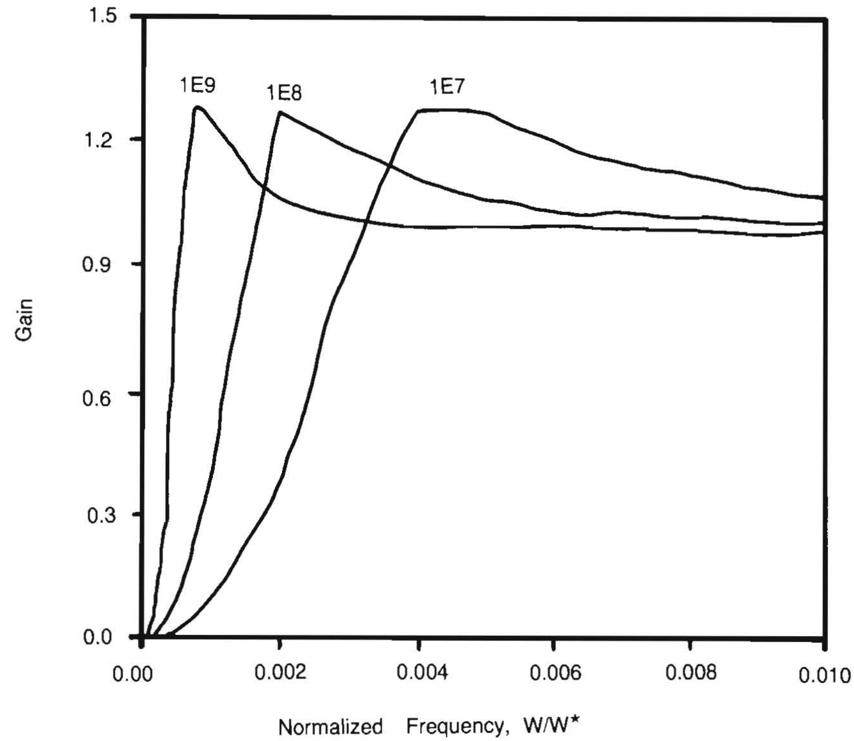

Fig. 12. The Effect of the Operating Input Frequency (f) on the Calculated Gain (A) Versus the Normalized Frequency (n = W/W*).

2 - Dependence on the Operating Bias Voltage:

Variations in operating bias voltage (U_o) affect the measured gain of tunnel-diode amplifiers. The (U_o) chosen to be at the middle of the negative dynamic resistance region in the volt-ampere characteristic curves plotted at room temperature. So, its value will depend on both (Stupelman and Filaretov 1976) the peak and valley voltages (V_p and V_v) which in turn depend on the values of Fermi levels in both two regions n-and p-type, as shown in Equ's.1 and 2. The effect of the operating bias voltage (U_o) on the measured gain (A), was investigated for GaAs tunnel diode of the type Au301A. The gain is shown to increase linearly with the increase in the applied bias voltage (with a correlation coefficient value of 0.96), as shown in Fig. 13.

Effect of Normalized Parameters of Tunnel
Diode on the Calculated Gain:

Theoretical analysis was extended in order to show the effect of the normalized parameters of the devices on the amplifier, in order to obtain the optimum circuit

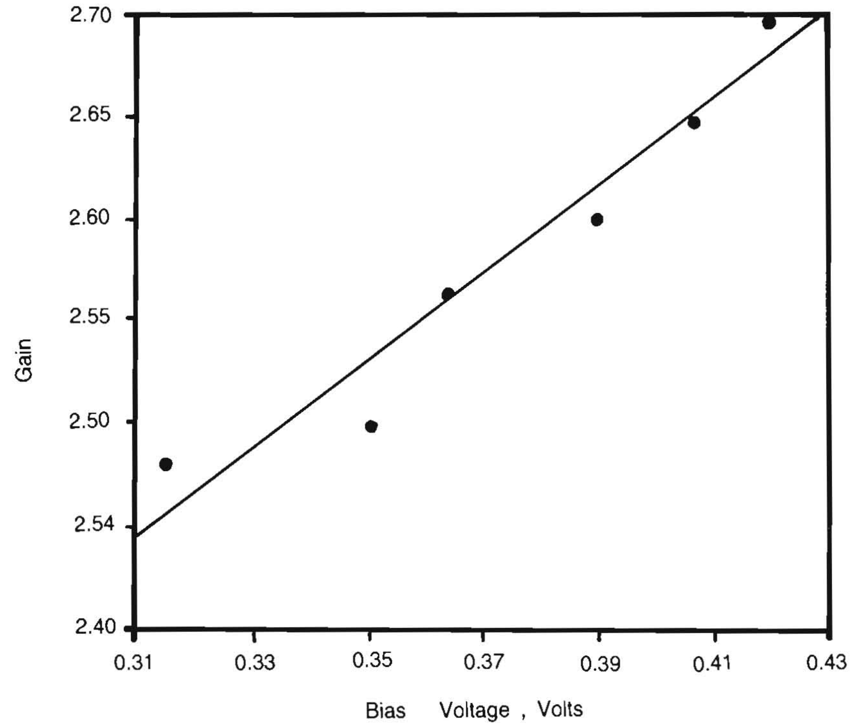

Fig. 13. The Effect of the Operating Bias Voltage (U_o) on the Measured Gain (A) Using T.D. of the Type Au 301 A.

parameters for a peak gain. The normalized parameters are: $M = r_o/R_o$ and $Q = C_D/C_c$.

1 - Dependence of the Gain on the Parameter $M = r_o/R_o$

Figuer (14) shows the dependence of the calculated gain on the normalized frequency ($N = W/W^*$) for different (M) values, while the rest parameters are kept constant, for tunnel diode type Au301A. It is clear from the figure that the calculated gain of the circuit amplifier is a function of the normalized parameter (M), *i.e.* on both the shunt resistor (r_o) and the dynamic negative diode resistance ($-R_o$). It increases as (M) increases, *i.e.*, with decreasing the negative dynamic diode resistance (−Ro). The calculated gains have their peak values at the same normalized frequency point ($N = 0.02$).

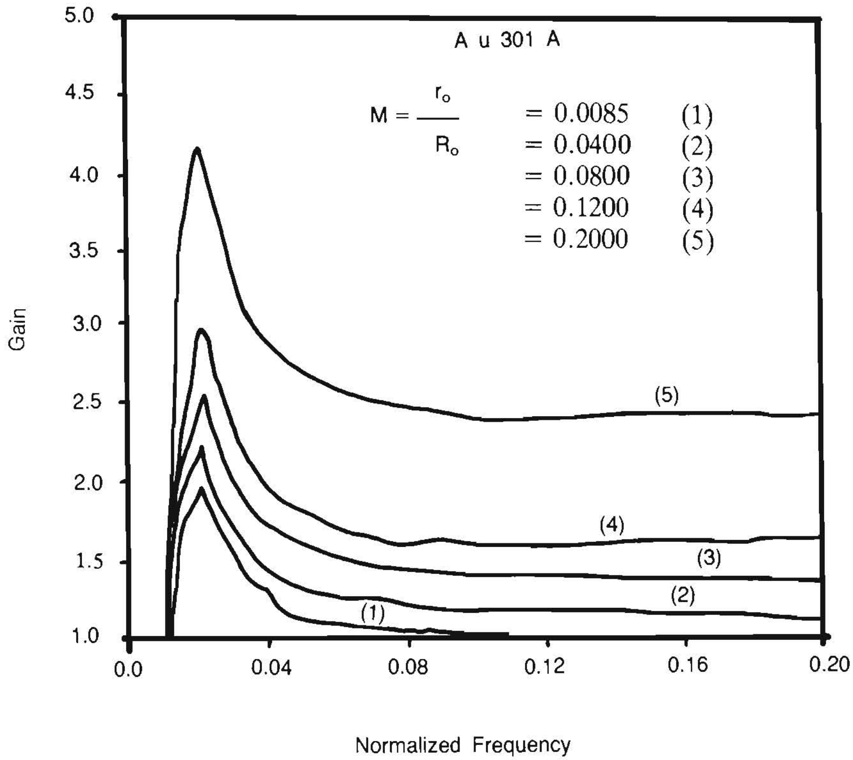

Fig.14. Dependence of the Calculated Gain on the Normalized Frequency (n = W/W*) for Different "M" Values while the Rest Parameters are Constant.

2 - Dependence of the Gain on the Parameter $Q = C_D/C_c$:

Figuer (15) shows the dependence of the calculated gain on the normalized frequency for different values of (Q), while the rest parameters are kept constant, for the same tunnel diode type. It is clearly seen that, the gain increases with the normalized frequency, reaching a peak point at a certain normalized frequency value, then decreases at higher frequency levels. The peak gain has almost the same value of "1.29" at different values of (Q). On the other hand, it tends to shift towards the higher frequency levels, as the (Q) ratio increase, *i.e.*, as the diode capacitor increases.

From the above results it is clear that, the gain of the tunnel diode circuit is a function of both the negative dynamic diode resistance ($-R_o$) and the shunt diode capacitor (C_D). The dependence on the diode capacitor is restricted only on the value of the normalized frequency at the peak gain.

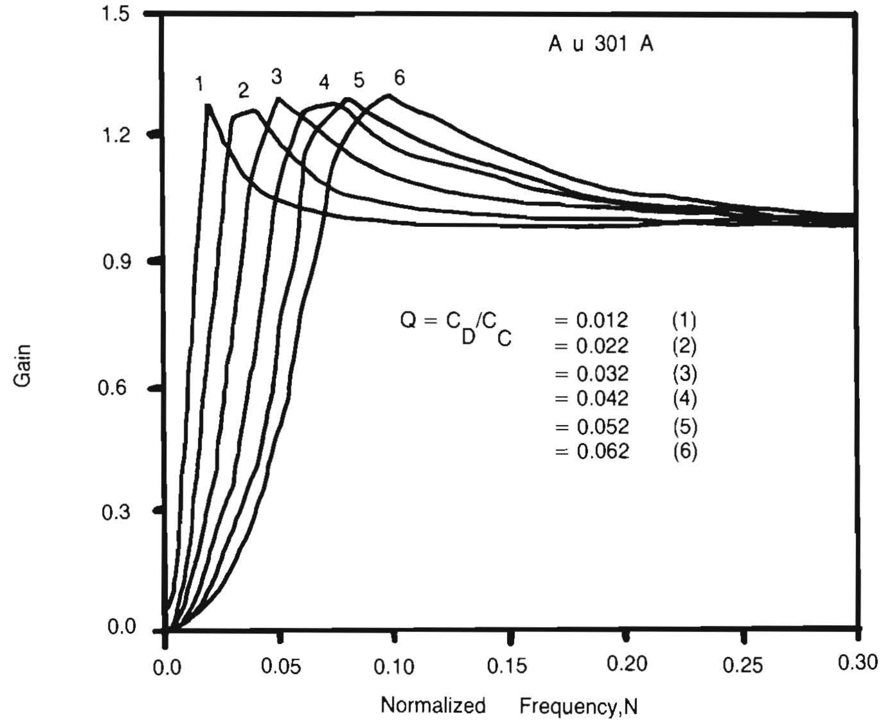

Fig. 15. Dependence of the Calculated Gain on the Normalized Frequency N = W/W* for Different Values of "Q" while the Rest Parameters are Constant.

Phase Angle, (φ):

The dependence of the phase angle (φ) of the amplifier circuit on the normalized input frequency (N = w/w*) was analyzed using both; GaAs (type Au301A), and InSb (type YΓ) tunnel diodes. This relation is shown in Fig. (16) for GaAs devices. It is clear from the figure that the phase angle (φ) has periodic dependence on the normalized frequency and it has values between O° and ± 90° for increasing the normalized frequency. This regular changing apply equally well, with the two diode types.

Appendix: Tunnel Diode Amplifier Circuit analysis

The following program has been constructed by the authors in order to carry out the calculations of the effective value of the gain of tunnel diode amplifier circuit, frequency response and the phase angle, using different device-and operating-parameters. Here follows the definitions of the symbols used in the proposed program.

$IP = I_p$; $IV = I_v$; $VP = V_p$; $VV = V_v$; $VFP = V_{Fp}$

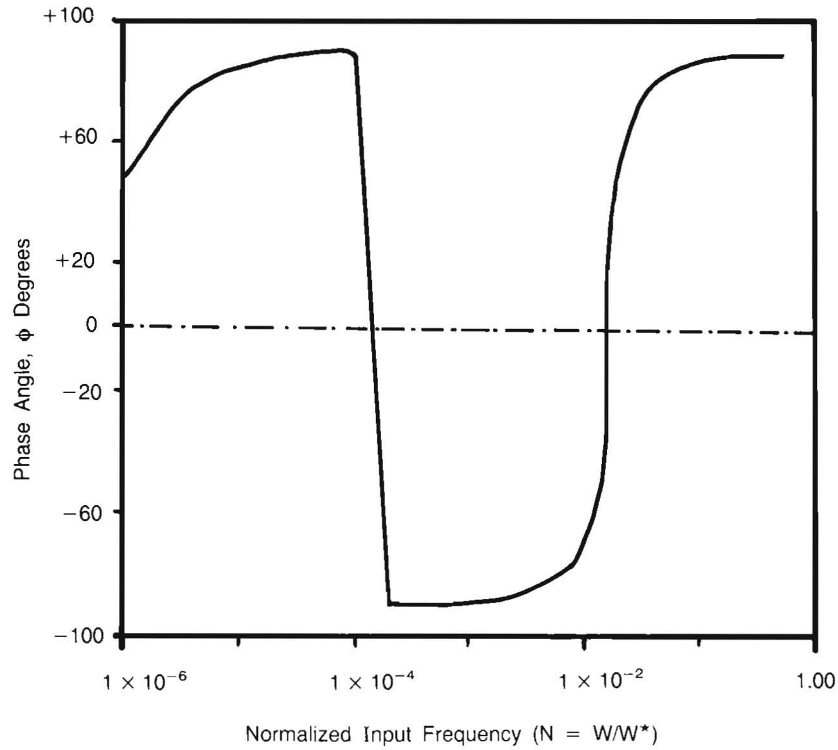

Fig. 16. Dependence of the Calculated Phase Angle φ on the Normalized Frequency (n = W/W*) for the Amplifier Circuit.

RL = R_L ; RG = R_g; CD = C_D; LS = L_s; FI = F_o
VSW = $V_{FP} - V_P$; FR = F_r; RD1 = effective resistance; FC = F_c;
RD = shunt resistor; RM = min. negative resistance
RNR = negative resistance

From the circuit shown in Fig. (17) one can obtain:

$$Z_1 = Z_z = Z$$

$$Z_{eq} = Z_z // Z_L \quad \text{.......} \quad (1)$$

$$I = I_1 + I_2 \quad \text{.......} \quad (2)$$

$$V_g = I\,(Z_g + Z_c) + (I_1 - I_2)\,Z_1 \quad \text{.......} \quad (3)$$

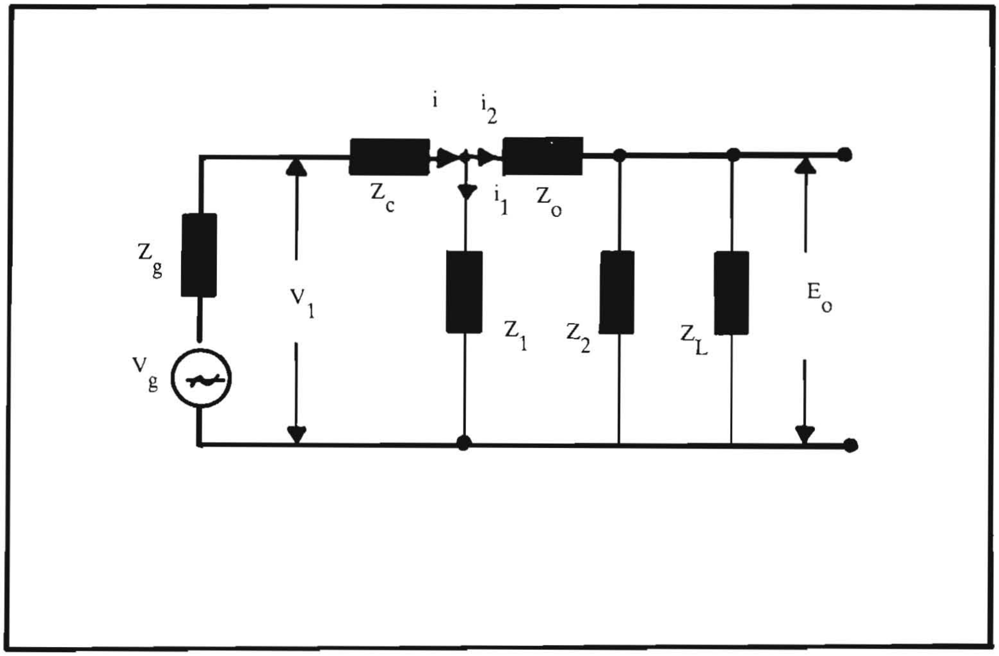

Fig. 17. Equivalent Circuit of Tunnel Diode Amplifier.

From Equ's. (2) and (3)

$$I_z . (Z_o + Z_{eq}) - (I_1 - I_2). Z_1 = 0 \quad (4)$$

$$V_g = I_1 (Z_g + Z_c + Z_1) + I_2 (Z_g + Z_c - Z_1) \quad (5)$$

$$I_2 = (I_1 . Z_1) / (Z_o + Z_{eq} + Z_1) \quad (6)$$

From Equ's. (5) and (6)

$$I1 = [V_g \cdot (Z_o + Z_{eq} + Z_1)] / [(Z_q + Z_c + Z_1) (Z_o + Z_{eq} + Z_1) + Z_1(Z_g + Z_c - Z_1)] \quad (7)$$

$$I2 = [V_g . Z_1] / [(Z_g + Z_c + Z_1)(Z_o + Z_{eq} + Z_1) + Z_1(Z_g + Z_c - Z_1)] \quad (8)$$

$$E_o = I_z . Z_{eq} = [V_g Z Z_{eq}] / [(Z_q + Z_c + Z)(Z_o + Z_{eq} + Z) + Z(Z_g + Z_c - Z)] \quad (9)$$

$$A = E_o/V_g = [Z.Z_{eq}] / [(Z_g + Z_c + Z)(Z_o + Z_{eq} + Z) + Z(Z_g + Z_c - Z)] \quad (10)$$

$$= [Z.Z_{eq}] / [2ZZ_g + 2ZZ_c + Z_gZ_o + Z_gZ_{eq} + Z_cZ_o + Z_cZ_{eq} + ZZ_o + ZZ_{eq}] \quad (11)$$

$$= Z^2.Z_L] / [2Z^2Z_g + 2Z^2Z_c + 3ZZ_gZ_L + 3ZZ_c^2Z_L + ZZ_o + Z^2Z_L + Z_gZ_oZ + Z_cZ_oZ + Z_gZ_oZ_L + Z_cZ_oZ_L + ZZ_oZ_L)] \quad (12)$$

$$\left.\begin{aligned} Z &= JwL_c\text{: impedance of the inductive coil} \\ Z_g &= R_g\text{: signal generator impedance} \\ Z_c &= 1/Jwc_c \\ Z_L &= R_L \\ Z_o &= r_o R_o /((R_o - r_o) + JW\, C_D\, r_o\, R_o) \\ &= \text{series impedance of the T.D. circuit} \end{aligned}\right\} \quad (13)$$

From Equ's. (12) and (13) :

$$A = [((1-r_o/R_o) + JWC_Dr_o)] / [((2R_g/R_L) - (2R_gr_o/R_LR_o) + (2C_Dr_o / 2C_DR_L) + (3R_gC_Dr_o/L_c) - (3W^2/ L_cC_c) + (3r_o/W^2L_cC_c/R_o) + (r_o/R_L) + 1 - (r_o/R_o) - (r_o/W^2L_cC_cR_L) - (r_oR_g/WL_c^2C_c) + J((2WR_g\, C_Dr_o/R_L) - (2/WC_cR_L) + (2r_o/WC_cR_LR_o) - (3R_g/WL_c) - (3C_Dr_o/WL_cC_c) + (3R_or_o/WL_cR_o) + (WC_Dr_o) - (R_gr_o/WL_cR_o) + (r_o/W^3L_c^2C_c) - (r_oR_o / WL_c))] \quad (14)$$

$$A = B + JC / D + JE$$
$$= [(BD + CE) / (D^2 + E^2)] + J [(CD - BE) / (D^2 + E^2)] \quad (15)$$

$$= \propto + J\,\beta \quad (16)$$

The effective gain value $| A | = \sqrt{\propto^2 + \beta^z}$ .... (17)
The phase shift between the output and input signals = (φ),
where:

$$\varphi + \tan^{-1} (\beta/\propto) \quad (18)$$

For computer programming, we had normalized the terms in Equ. 14 as follows:

$M = r_o/R_o$; $N = W/W^*$; $X = R_g/R_L$; $Q = C_D/C_c$;

$W^* = 1/C_D.R_o$; $S = L_c/C_c.R_L^2$; $p = r_o/R_L$; $Y = R_o/R_L$ .... (19)

Corresponding to the parameters of the diode type Au301A and the parameters of the amplifier circuit; ro = 1 ohm; Rg = 75 ohm and R_L = 10 K. ohm

```
10    REM PROG TD
20    OPTION BASE 1
30    L = 8E-09
50    IP = 1.705
60    LC = .0005
70    CC = 5E-11
80    LPRINT"LC = ":LC:".CC = ":CC
90    VP = .24
100   IV = .04
110   VV = .6
120   CD = 1.2E-11
140   VFP= 1.13
150   LPRINT"IP = ":IP:"VP = ":VP
       :"IV = ": IV:":VV = VV
170   LPRINT" CD = CD ":L = ":L
190   INPUT N
200   RD = 1
210   RL = 10000!
220   FI = 10000000 #
230   LPRINT "FI = ":FI
240   RG = 75
250   CD = 1.2E-11
260   LPRINT"RD = ":RD:"RL = "
       :RL:"FI = ":FI
270   LPRINT"CD = ":CD
280   PI = 3.14159
290   R = VV/VP
300   LPRINT"VALLEY TO PEAK
       VOLTAGE RATIO = ": R
320   RX = IP/IV
330   LPRINT"PEAK TO VALLEY
       CURRENT RATIO = ": RX
340   RM = (2) * (VP/IP)
350   LPRINT"MIN. NEGATIVE
       RESISTANCE = ": RM
370   VSW = VFP-VP
380   LPRINT"VOLTAGE SWING
      = ": VSW: "VOLT"
390   PR = (.12) * (VV-VP) *
       (IP-IV)
400   LPRINT"POWER = ":PR:"WATT"
420   RNR = (200)/(IP)
430   LPRINT"NEGATIVE RESISTANCE = ": RNR

450   A = (CD)*(RNR)*(RNR)
460   BA = (A)-(L)
470   CA = (BA)/(L)
480   DA = SOR (CA)
490   DA1 = (DA)/((2)*(PI)*(CD)*(RNR))
```

```
500     FS = DA1
510     LPRINT"SELF RESONANT
         FREQUENCY = ":FS: "HZ"
530     EA = RNR-RD
540     FA = EA/RD
550     GA = SOR (FA)
560     HA = (2) * (PI) * (CD) * (RNR)
570     FR = (1/HA) * (GA)
580     LPRINT"RESISTIVE CUT OFF
        FREOUENCY = ":FR:"HZ"
600     JA = ((2) * (PI) * (FI) * (CD)* (RNR)) ^ (2)

610     KA = JA + 1
620     RDI = RNR/(KA)
630     LPRINT"EFFECTIVE RESISTANCE = ": RD1

640     Y = RD1/RL
650     M = RD/RD1
660     S = (LC)/(CC* (RL ^ 2))
670     W = (2) * (PI) * (FI)
680     WI = (1)/((CD) * (RD1)
690     Q = CD/CC
700     LPRINT "Q = ":Q
710     X = RG/RL
720     LPRINT"Y = ":Y:"M = ":M: X = ":X
740     S = (LC)/(CC * (RL ^ 2))
750     P = RD/RL
760     B = 1-(M)
770     C = (N) * (M)
780     A7 = 1/N
790     A1 = 3* X* Q * P/S
800     LPRINT"W = ":W:"W1 = ":W1
         :"N = ":N:"Q = ":Q
810     LPRINT"S =  ":S:"P = ":P  "B":B:"C = ":C

830     A3 = 3*M*(Q) ^ (2)*(Y) ^ (2)/S
840     A4 = 3*(Q) ^ (2)*(Y) ^ (2)/S
850     A5 = P*(Q) ^ (2)*(Y) ^ (2)/S
860     A6 = (P) *X*(Q) ^(2)*(Y) ^(2)
870     A2 = 1/((N) ^ (3))
880     D  = N*(A7*(1-M + P + (2*X) - (2*X*M)
            + (2*Q*P) + A1) + A2*(A3-A4-A5-A6)

890     B1 = M + ((2)*(M)*(X))
900     B2 = 1/((N) ^ 2)
910     B3 = ((3)*(X)*(Q)*(Y))/(S)
920     B4 = ((3)*(X)*(M)*(Q) *(Y))/(S)
940     LPRINT"D = ":D
960     B5 = ((3)* ((Q) ^ (2))*
```

```
        (P)* (Y))/(S)
970     B6 = ((X)* (P)* (Q)* (Y))/(S)
980     B7 = ((P)*(Q)*(Y))/((S)
990     B8 = 1/((N)^4)
1000    B9 = (P)*((Q)^(3))* ((Y)^(3))/((S)^2)

1010    E = N*(B1 + B2*((2)*(P)*(Q) -
            (2)*(Q)*(Y) - B3 + B4 - B5 - B6 - B7) + (B)

1020    X1 = ((M)^(2)) + ((2)*((M)^(2))*(X))
1030    C1 = (4)*(X)*(M)
1040    C2 = (2)*(P)*(Q)
1050    C3 = (2)*(X)*((M)^(2))
1070    LPRINT"E = ":E
1090    C4 = (P)*(M)
1100    C5 = (2)*(Q)*(Y)*(M)
1110    C6 = (3*X*Q*P)/(S)
1120    C7 = (3*X*Q*P*M)/(S)
1130    C8 = (3*X*Q*Y*M)/(S)
1140    C9 = (3*X*(M^2)*Q*Y)/(S)
1150    D1 = (3*(Q)^(2)*P*Y*M)/(S)
1160    D2 = (X*P*Q*Y*M)/(S)
1170    D3 = (P*Q*Y*M)/(S)
1180    K  = 1 - 2*M + (M)^(2) - C + 2*X + C2
            + P + C3 - C4 - C5 + C6 - C7 - C8 +
            (C9) - (D1) - (D2) - (D3)
1200    D4 = 6* M*(Q)^(2)*(Y)^(2)/S
1220    LPRINT"
1230    D5 = 3*(Q)^(2)*(Y)^(2)/S
1240    D6 = P* (Q)^(2)*(Y)^(Y)^ S
1250    D7 = 3*(M)^(2)*(Q) ^(2)*(Y)^(2)/S
1260    D8 = P*(Q)^(2)*(Y)^(2)*M/S
1270    D9 = P*X*(Q)^(2)*(Y)^(2)*M/S
1280    E1 = P*X*(Q)^(2)*(Y)^(2)/(S)^(2)
1290    E2 = P*(Q)^(3)*(Y)^(3)*M/(S)^ (2)

1300    Z  = D4 - D5 - D6 - D7 + D8 + D9 - E1 + E2

1310    E3  = (M)*(P)
1320    LPRINT"D5 = ":D5:" D6 :"D6 = ":D7 = ":D7:"D8 = ":D8

1330    LPRINT"D9 = ":D9:"E1 = :"E1:"E2 = ":E2:"E3 = ":E3

1350    LPRINT"Z = ":Z
1370    E4 = (2)*(Q)*(P)*(M)
1380    E5 = (3)*(X)*(P)*(Q)*(M)/(S)
1400    L1 = E3 + E4 + E5
1420    E6 = (2)*(Q)*(Y)
```

```
1430   E7 = 2*P*Q
1440   E8 = 2*Q*Y*M
1450   E9 = 2*P*Q*M
1460   F1 = 3*(Q) ^ (2)*(Y) ^ (2)*M/S
1470   F2 = 3*(M) ^ (2)*(Q) ^ (2)*(Y) ^ (2)/S
1480   F3 = P*(Q) ^ (2)*(Y) ^ (2)*M/S
1490   F4 = P*X*(Q)^(2)*(Y)^(2)*M/(S)^(2)
1500   F5 = 3*X*Q*Y/S
1510   F6 = 6*M*X*Q*Y/S
1520   F7 = 3*(Q) ^ (2)*P*Y/S
1530   F8 = X*P*Q*Y/S
1540   F9 = P*Q*Y/S
1550   G1 = 3*X*(M) ^ (2)*Q*Y/S
1560   G2 = 3*(Q) ^ (2)*P*Y*M/S
1570   G3 = X*P*Q*Y*M/S
1580   G4 = P*Q*Y*M/S
1590   02 = E6 - E7 - E8 + E9 - F1 + F2 - F3
          - F4 + F5 - F6 + F7 + F8 + F9 + G1 -
          G2 - G3 - G4
1600   G5 = P*(Q) ^ (3)*(Y) ^ (3)*M/(S) ^ (2)
1610   G6 = P*(Q) ^ (3)*(Y) ^ (3) /(S) ^ (2)
1620   GAMMA = (G5) - (G6)
1630   ALF1 = ((B)*(D)) + ((C)*(E))
1640   BET1 = ((C)*(D)) - ((B)*(E))
1650   DEM = ((D) ^ (2)) - ((E) ^ (2))
1660   DEM1 = 1/(DEM)
1670   GAIN = DEM1*SOR((ALF1) ^ (2) + (BET1) ^ (2))

1680   LPRINT"ALF1 = ":ALF1:"BET1 =
       ":BET1:"DEM = ":DEM
1690   V1 = ((N) ^ (2))
1700   V2 = X1
1710   V3 = K/(N ^ (2))
1720   V4 = Z/(N ^ (4))
1730   ALF2 = (V1)*(V2 + V3 + V4)
1740   BET2 = (V5)*(V6 + V7 + V8)
1750   LPRINT"ALF2 = ":ALF2
1760   V5 = N
1770   V6 = L1
1780   V7 = 02/(N ^ (2))
1790   V8 = GAMMA/(N ^ (4))
1800   BET2 = (V5)*(V6 + V7 + V8)
1810   GAIN = SOR((ALF2) ^ (2) + (BET2) ^ (2)) *DEM1

1820   LPRINT"GAIN = ":GAIN
1830   LPRINT"BET2 = ":BET2
1840   FAI = (ATN(ALF2/BET2))/(3.14/180)
1850   LPRINT" FAI = ":FAI
1860   END
```

Conclusions

In the present work a computer program is developed for easy use for investigating the effects of various physical parameters and circuit elements on tunnel device circuit as an amplifier. From the study, analysis, experimental and theoretical results obtained, following conclusions can be deduced:

- The gain of circuit amplifier exceeds unity.
- The gain increases with the frequency, reaching a peak at certain value of the frequency, then it decreases, at higher frequencies, down to a constant plateau value.
- The peak gain of the tunnel amplifier depends on:

  a. Device physical parameters (C_D, $-R_o$ and device material).
  b. Circuit parameters (L_C, C_C, R_L, r_o).
  c. Operating conditions (U_o, F_o).

- The shape of the gain-frequency dependence is a function of the dynamic negative resistance ($-R$), frequency, and the resonance nature of the circuit (L_c, C_c).
- The amplitude characteristics of the circuit amplifier, measured at peak frequency, is linear.

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التحليل الرياضي بالحاسبات الآلية لتصميم دائرة مكبر ذات نطاق ضيق بإستخدام ثنائيات الاختراق

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أجريت دراسة رياضية وتم وضع مقترح نموذج وبرمجة معادلاته وتنفيذه على الحاسبات الألكترونية الشخصية وذلك لتصميم دائرة مكبر ذات نطاق ترددات ضيق وتعمل في مدى الترددات العالية بإستخدام ثنائيات الإختراق.

ساعد البرنامج المقترح على دراسة واختبار العوامل المختلفة المؤثرة في الخواص الأساسية للمكبر مثل معامل التكبير للنظام ومنحنيات الإستجابة وتحديد كل من ترددي التذبذب الذاتي والقطع وكذلك زاوية وجه المكبر.

من أهم العوامل التي تم دراستها هي الخصائص الأساسية للنبائط (سعة الرابطة الثنائية ـ المقاومة الداخلية الفعالة ـ نوع مادة النبائط ـ طريقة التصنيع وكثافة تركيز الشوائب) أو مكونات الدائرة الكهربائية المقترحة (الحث الذاتي والسعة لدائرة الرنين وكذلك مقاومة الحمل). ذلك بالإضافة إلى ظروف تشغيل دائرة المكبر المقترحة.

البرنامج المقترح وضع بلغة الباسيك والتي يسهل استخدامها سواء على الحاسبات الالكترونية الشخصية أو أي آلة حاسبة مبرمجة صغيرة.

إمتدت الدراسة كذلك للتطبيق العملي على دائـرة المكبر المقتـرح رياضيـا، وقد وضع التصميم العملي لهذه الدائرة بناءاً على أفضل النتائج التي تم تسجيلها في النموذج الرياضي.

وقـد درست العلاقـة العملية بـين خواص دائـرة المكبر وكـل من العوامـل السابقة بإستخدام نـوعين من ثنـائيات الاختـراق المصنعة من جـاليوم أرسينـايد (Ga As) أو الانديوم انتيمونيد (In Sb) وقد وجد أن قيمـة معامـل تكبير الـدائرة المقترحة تتعدى الوحـدة وتعتمد إعتمـاداً طرديـاً على العـلاقة بـين تياري القمـة والقاع لمنحنيات الخـواص الاستاتيكيـة للنبائط (I_p/I_v) والقيمـة المطلقـة لكل من تيـار وجهد القمـة (I_p,V_p) وكذلـك المقاومـة التفاضليـة السالبـة وأقل قيمـة لهـا ($-R_o/R_m$). كما وجد ان معامل التكبير دالة عكسية في العلاقة بين جهـدي القاع والقمـة (V_v/V_p). وقيمة تيـار القاع (I_v)، بـالإضافـة إلى نـطاق تـأرجـح الجهـد.

توصلت الدراسة النظرية والعملية إلى التعرف على العوامل المؤثرة في شكل منحنيات الإستجابة والسعة لدائرة المكبر مثل المقاومة التفـاضلية السـالبة وتـردد التشغيل وكذلك طبيعة دائرة الرنين.

كانت النتائج العملية والرياضية في تطابق تام مما يعطي انطبـاعا جيـدا على نجاح النموذج الرياضي المقترح طبقا لبرنامج الحاسب الآلي المستخدم.