COMPUTER ANALYSIS FOR DESIGNING NARROW - BAND TUNNEL DIODE AMPLIFIER CIRCUIT

By F.A.S. SOLIMAN* and S.A. KAMH**

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 developing efficient and economical computer programs which incorporate all of the important material parameters and doping levels in an exact manner. These computer programs are then employed to study the properties of tunnel diodes in high frequency amplification circuits. Some very interesting properties of these devices and the effests 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. Preliminary calculations have also been carried out on different GaAs and InSb tunnel diodes and the results are presented. Experimental measurements of the characteristics of the amplifier show good agreement with those obtained theoretically.

INTRODUCTION

The tunnel diode invented by "Leo Esaki" in 1958 [1], 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 conditons; the contact potential is large; the space–charge region is very narrow and the field in this region is extrecly high [2–4]. The aim of this work is to suggest a computer program to solve the general equations for the devices and to iatroduce the effect of device physical parameters, circuit terms, operating conditions upon their performance as a high frequency amplifier, as well as, to compare the calculated results with those obtained experimentally.

Static Parameters of Tunnel Diode

Tunnel diodes belong to the devices exhibiting a negative differential conductance (NDC) which enables the tunnel diodes to amplify and

---

* Nuclear Material Authority, Maadi P.O. Box 530, Cairo, Egypt.
** Faculty of Women for Arts, Science and Education, Ain -Shams University, Cairo, Egypt.

generate signals [5]. 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 5 % 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
intil the overlapping reaches a maximum. The maximum overlap sets
in, when the forward voltage.

$$V_P = (E_{Fn} + E_{FP}) / 3 \, q \tag{1}$$

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

$$V_V = (E_{FP} + E_{Fn}) / q \tag{2}$$

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). Voltages (V_P) and (V_V) depend
on the values of (E_{FP}) and (E_{Fn}), i.e., on the degree of doping of the
p–and n–region of a semiconductor [6]. Valley curent, also called excess
current, depends on the density of levels in a semiconductor baad gap,
which are responsible for the presence of the tunneling current at vol-
tages higher than (V_V). The larger the number of energy levels in the
baad gap, the higher the valley current. On the other hand, voltage
(V_{FP}) depends on the width of a semiconductor band gap.

A major property exhibited by the tunnel diode, allowing it 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.

$$-R_0 \, (ohm) = 200 / I_P \, (for \, GaAs–diodes) \tag{3}$$

and the diode will function as an amplifier when the condition $| R_0^- |
> | R_L |$ is satisfied. Otherwise, the stability of the tunnel diode nega-
tive resistance will become dependent on the external resistance.

Tunnel Diode Dynamic Parameters

Two dynamic parameters [6–8] which are useful in the selection
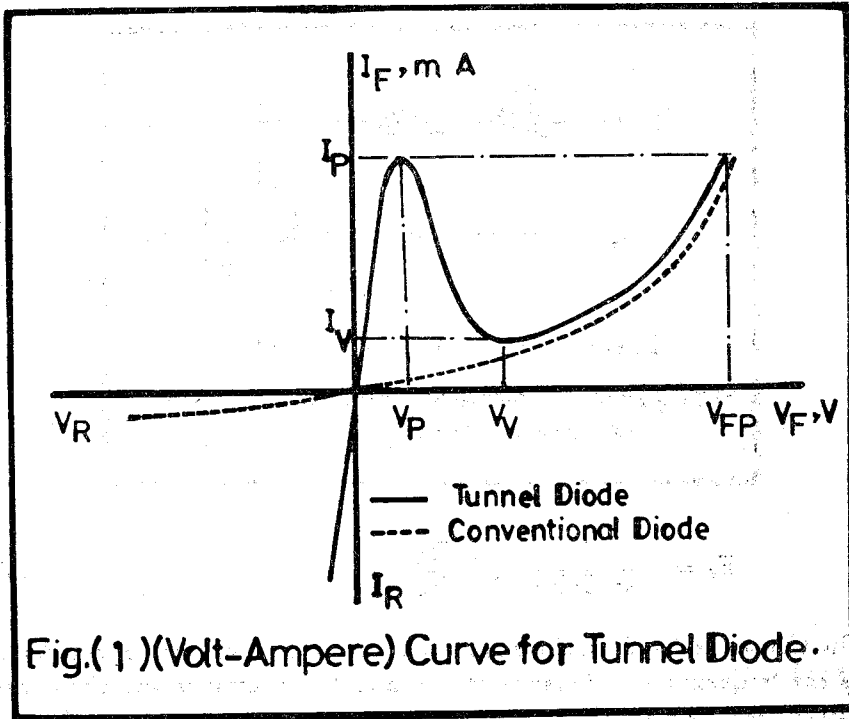of tunnel diodes for different applications are the resistive cut–off

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

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 [7], across the terminals "a", "b" is as shown in Fig. (2).

$$Z = R_s - \frac{R_0}{1 + (wC_D R_0)^2} + Jw \left(L_s - \frac{C_D}{(1/R_0)^2 + (wC_D)^2} \right). \quad (4)$$
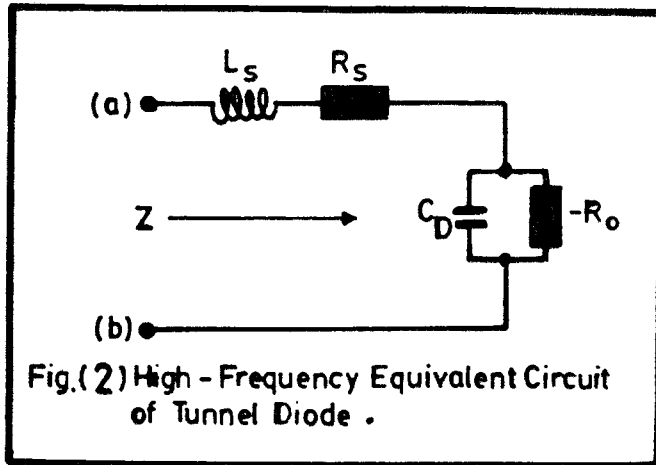
where:

   R_s : Total series resistance,

   L_s : Self inductance of leads,

   C_D : Diffusion capacitance.

   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 [5].

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

$$F_c = \frac{1}{2\pi\, C_D R_O} \sqrt{\frac{R_O}{R_s} - 1} \tag{5}$$

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

$$F_r = \frac{1}{2\pi\, C_D R_O} \sqrt{\frac{C_D R_O^2}{L_s} - 1} \tag{6}$$

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 capacitance (C_D)
of the diode. The following equation permits calculation of the effec-
tive negative resistance at any particular operating frequency [5].

$$R_O^- = R_O / (1 + (2\,\pi\, F_o C_D R_o)^2) \tag{7}$$

Experimental Procedures:
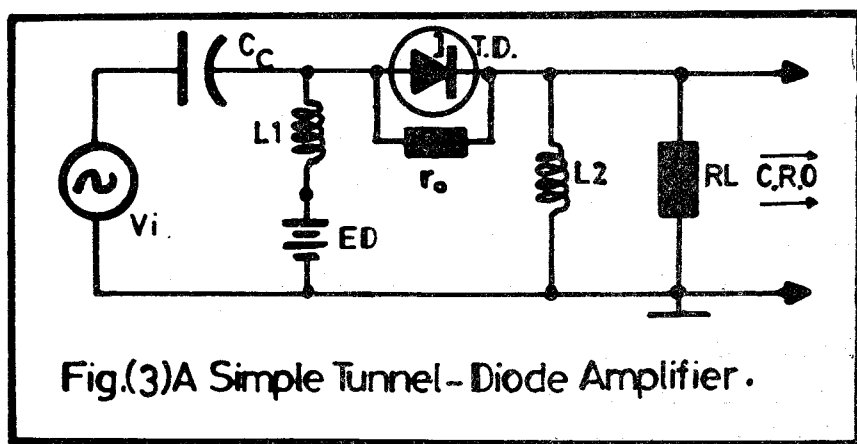
1. Dc- Characteristics

In order to investigate the factors that affect the gain of tunnel
diode amplifier, six different types of GaAs tunnel diodes namely:

3N301B, AN301r, Au301A, AN301Γ, AN301σ and AN301A were sub-
jected to several tests in order to plot their output characteristics.
Besides, device material effects was also considered applying InSb
tunnel diode; type TΓ. Tektronics 577–177–D1 storage curve tracer,
which is a dynamic component tester was used in plotting the device
characteristics.

2. Amplifier Circuit Analysis

The tunnel diode [9, 10] 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 cas-
cading tunnel–diode amplifiers. For convenience, voltage amplification
will be discussed although a similar discussion could be applied to
current–or power–amplification.

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 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: $L_1 =
L_c = L_C = 25$ µH, $C_C = 1000$ pF, and $R_L = 10$ k. ohm.

Fig.(3)A Simple Tunnel-Diode Amplifier.

RESULT AND DISCUSSION

DC-Characteristics

Fig. (4) illustrates the (I–V) characteristics of two different tunnel diodes. Interesting feature of the two curves is the presence of the "NDC" region. This "NDC" devices can be used either as amplifier or oscillator in a wide spectrum of electronic systems. The physical basis [11, 12] for 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.
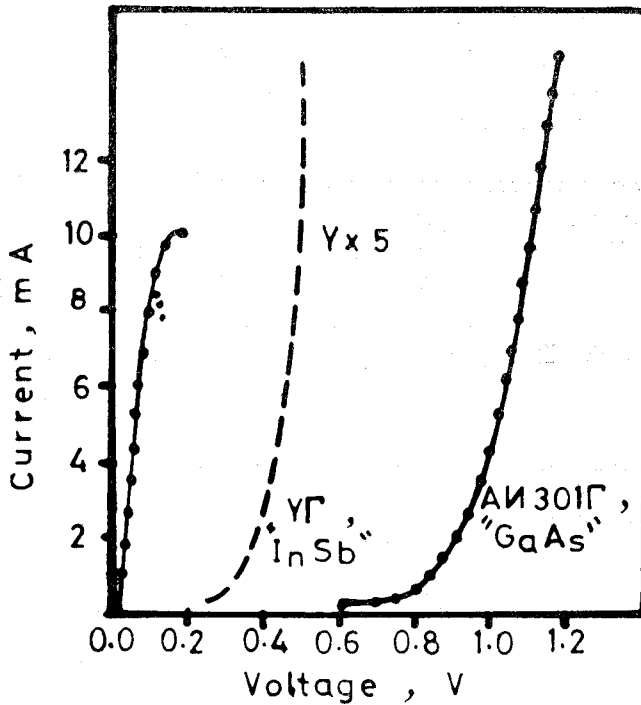

Fig. 4: Characteristics for two Different Tunnel Diode Types.

Response Characteristics

The dependence of the gain on the frequency was plotted at an input signal amplitude of 20 mV in the frequency range from 1 to 10 MHz. Moreover, the amplitude characteristics were measured at the frequency of the peak gain. Fig. (5a) shows the variations of the amp-

lifier 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 dfrequency, reaching a peak value, then decreases
at higher frequencies (narrow band amplifier). Fig. (5b) shows the ampl-
itude characreristics for the tunnel diode amplifier at the frequency of
the peak gain, where a linear relationship between input and output
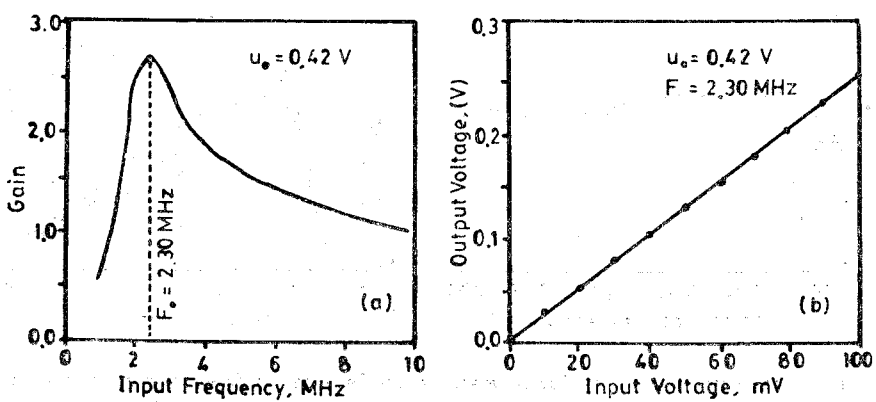signals, with a correlation coefficient of 0.99975, was achieved.

Fig. 5: (a) Gain-Frequency Dependence and (b) Amplitude Characteristics for the Amplifier.

Effect of Device Parameters

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 curtent, 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.

Effect of Device Material

The effect of the devices material on the amplifier response charac-
teristics were obtained theoretically and experimentally for both the
diode types Au301A (GaAs) and YF (InSb). The peak gain point of
the two devices occur at different frequencies (Fig. 6). 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 cal-
culated, for InSb samples. For all the tested devices, the peak gain for

GaAs diodes 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.
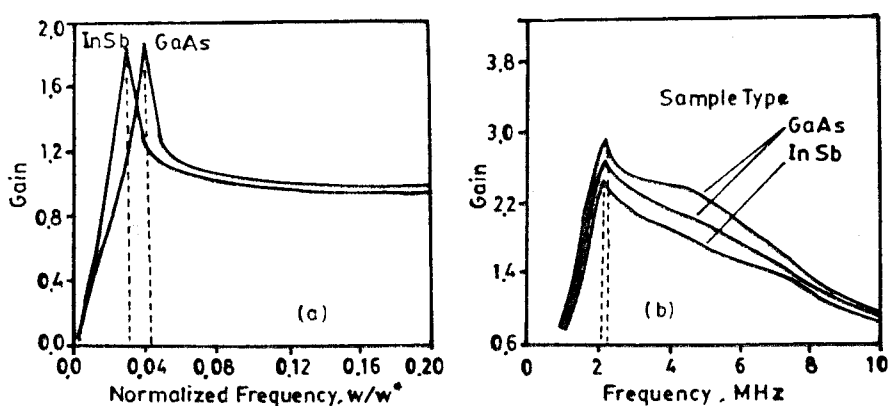

Fig. 6: Theoretical (a) and (b) Experimental Results Showing the Effect of the Devices Material on the Gain.

Effect of Circuit Parameters

a) L_c abd 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 values of the circuit capacitor (C_c) and inductor (L_c) were chosen to get the maximum gain [4, 11–14]. They where calculated at the operating input frequency of 1 MHz. Fig. (7) 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 x 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
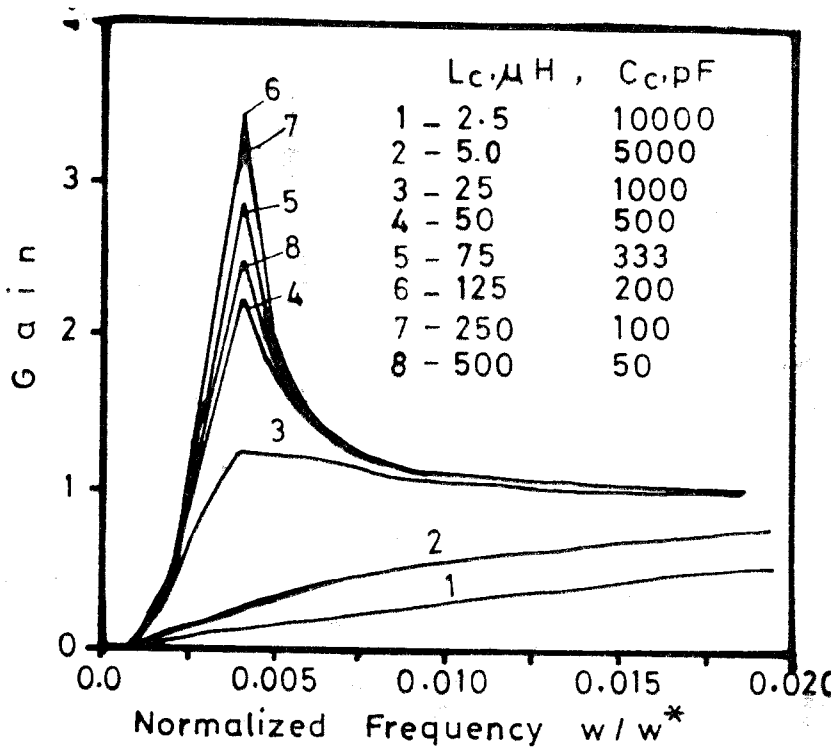
Fig. 7: Effect of Circuit Parameters (Ls,Cs) on the Calculated Gain of Tunnel Amplifier Circuit.

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 and the resulted gain was shown to be with a value of "1.22" which is in close agreement with that theoretically calculated.

b) Load Resistance

The theoretical calculations for the optimum condition of the maximum gain of circuit amplifier using tunnel diode of the type 3N301B shows that, the gain has greater values 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. 8).
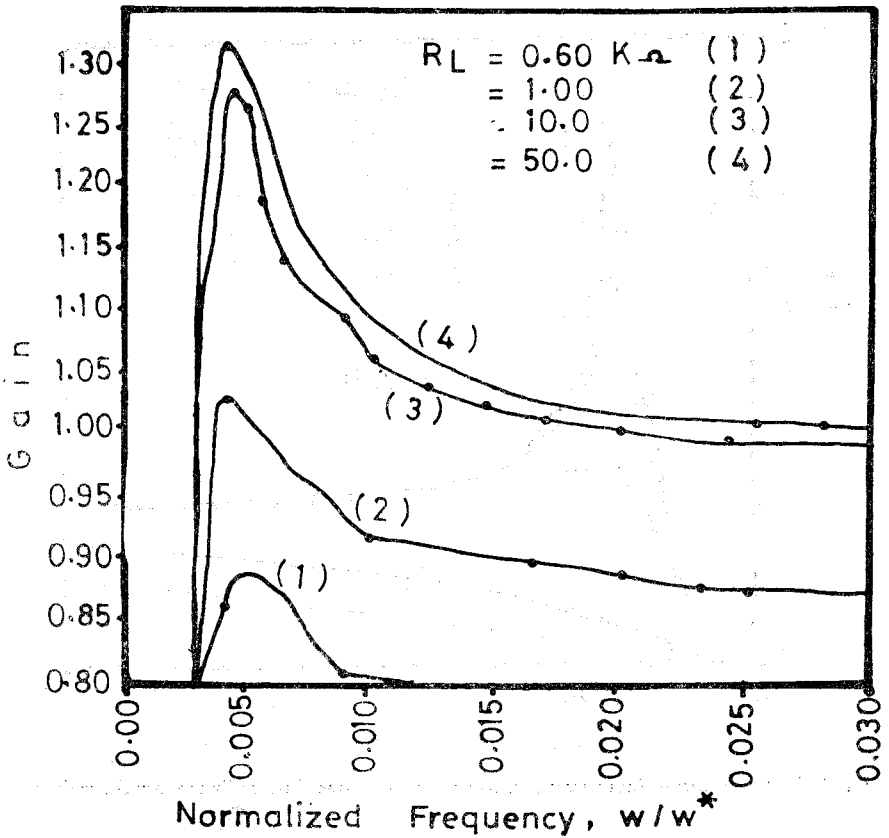
Fig. 8: Dependence of the Calculated Gain on the Normalized Frequency (n = w/w*) for Different Load Resistor Values.

Effect of Shunt Resistor

As pointed by ChirLian [9], a stable amplifier can be obtained if the tunnel diode in the cicuit is shunted by a small enough resistance. The magnitude of the appropriate shunt resistance (r_0) values are computed to get the maximum gain for the amplifier circuit using tunnel diod of the type 3 301B. The theoretical shunt resistance values adapted to calculations of gain appear to be in general agreement with those realized in practice. Fig. (9) shows the effect of the shunt resistance values on the calculated gain of the circuit amplifier, where resistance values range from 0.10 ohm up to 10 ohm was investigated. It is clear from the figure that as the shunt resistor (r_0) be small enough, less than 1 ohm, the gain will be high.
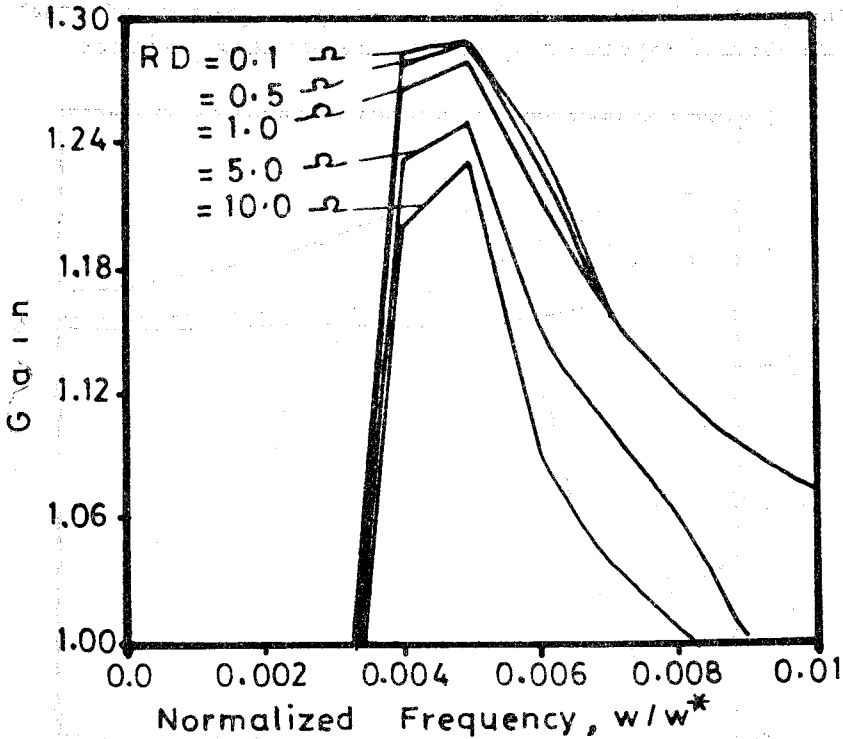
Fig. 9: Effect of Shunt Resistor on the Calculated Gain of the Circuit Amplifier.

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 frequency (N = w / w*) was studied for GaAs tunnel diode amplifier circuit. The study included, as shown in Fig. 10, three values of input frequencies: 10^7, 10^8 and 10^9 Hz, which corresponding to the: medium (short wases), 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 shokwn to be shifted toward lower normalized frequency values as the operating input frequency increases. This is so, the shape is function of the dynamic negative resistance ($-R_0$), 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 that results obtained experimentally at the same operating conditions.
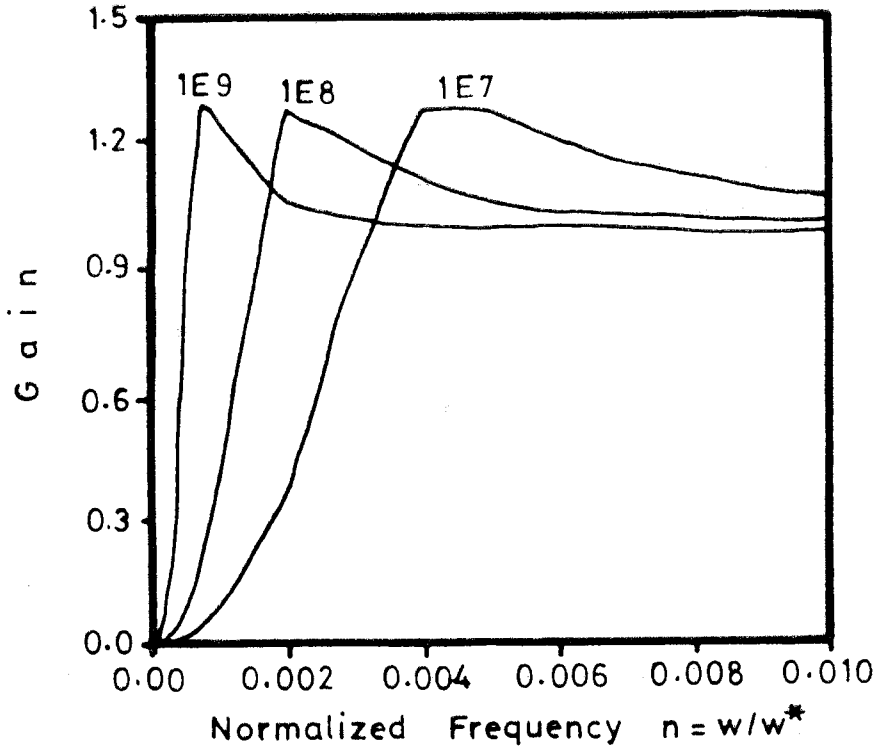

Fig. 10: The Effect of the Operating Input Frequency (f) on the Calculated Gain (A) Versus the Normalizd Frequency (n = w/w*).

2– Dependence on the Operating Bias Voltage

Variations in operating bias voltage (U_0) affect the measured gain of tunnel–diode amplifiers. The (U_0) was chosen to be at the middle of the negative dynamic resistance region. The gain is shown to increase linearly with the increase in the applied bias voltage (whith a correlation coefficient value of 0.96), as shown in Fig. 11.

Effeect of normalized Parameters of Tunnel
Diode on the Calculated Gain

The theoretical analysis w^re extended in order to show the effect of the normalized parameters of the devices on the amplifier in order
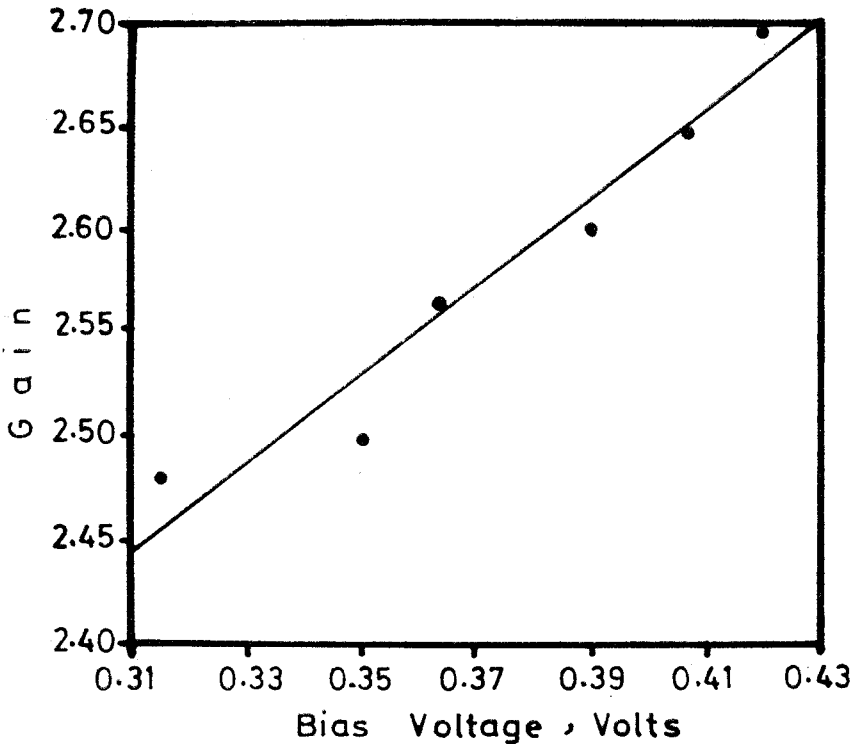
Fig. 11: The Effect of the Operating Bias Voltage (U$_z$) on the Measured Gain (A) Using T.D. of the Type Au 301 A.

to obtain the optimum circuit parameters for a peak gain. The normalized parameters are: $M = r_0 / R_0$ and $Q = C_D / C_C$.

1– Dependence on the Parameter $M = r_0 / R_0$

Figure (12) shows the dependence of the calculated gain on the normalized frequency ($N = c / w^*$) 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_0) and the dynamic negative diode resistance ($-R_0$). It incre ases as (M) increases, i.e., with decreasing the negative dynamic diode resistance ($-R_0$). The calculated gains have their peak values at the same normalized frequency point ($N = 0.02$).
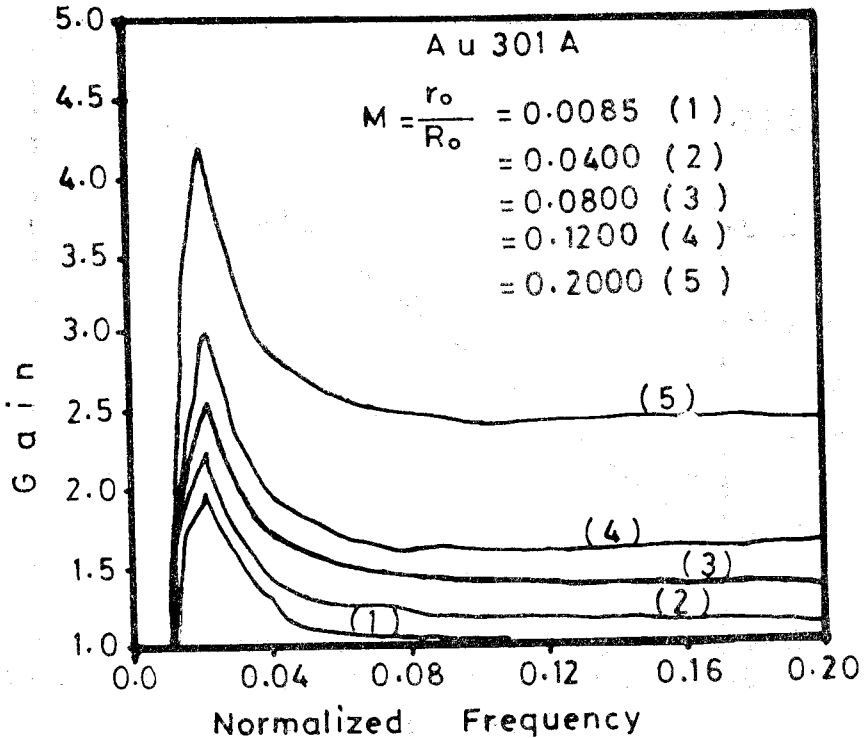
Fig. 12: Dependence of the Calculated Gain on the Normalized Frequency $(n = w/w^*)$ for Different M Values while the Rest Parameters are Constant.

2– Dependence on the Parameter $Q = C_D / C_C$

Figure (13) shows the dependence of the calculated gain on the normalized frequency for different values of (Q), while the rest parameter 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 balue, 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 $(-R_0)$ and the shunt diode capacitor (C_D). The dependence on the diode
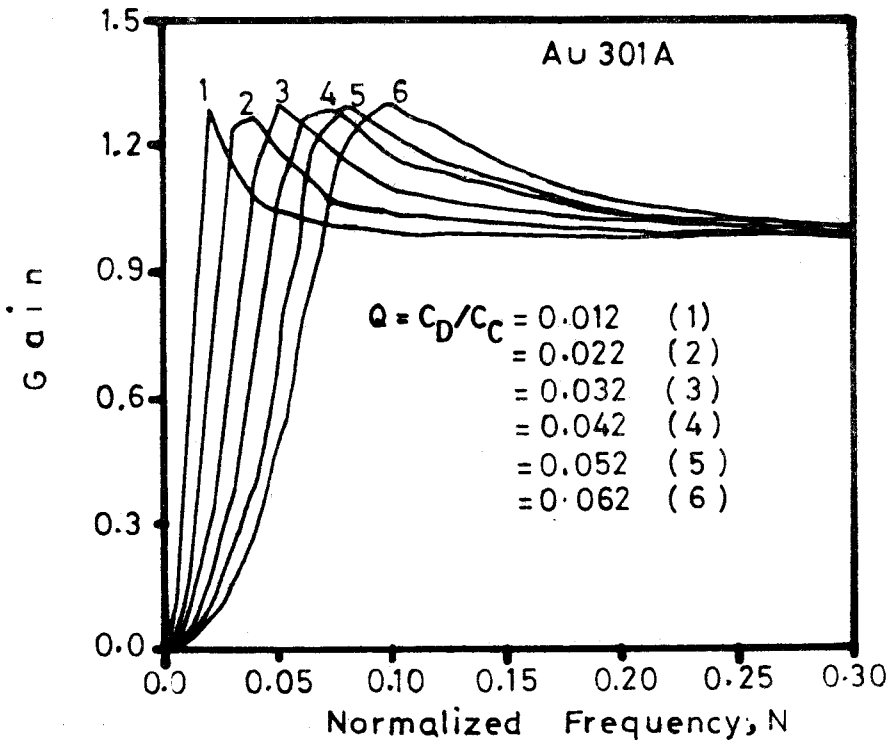
Fig. 13: Dependence of the Calculated Gain on the Normalized Frequency $N = w/w^*$ for Different Values of "Q" while the Rest Parameters are Constant.

capacitor is restricted only on the value of the normalized frequency at the peka gain.

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. (14) 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 netween $0°$ and $\pm 90°$ for increasing the normalized frequency. This regular changing apply equally well, with the two diode types.
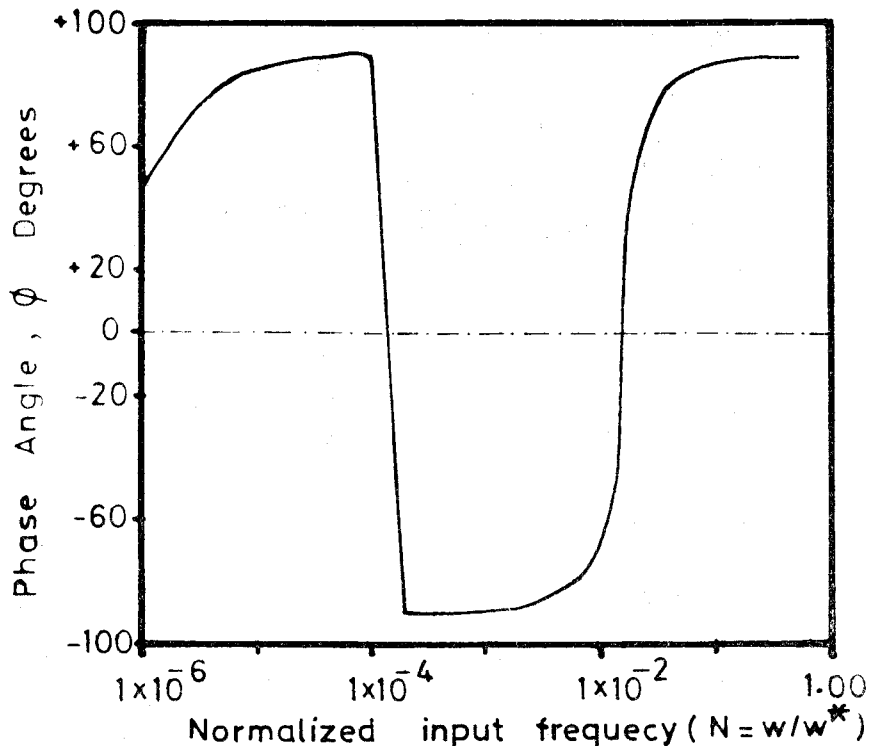
Fig. 14: Dependence of the Calculated Phase Angle Φ on the Normalized Frequency (n = w/w*) for the Amplifier Circuit.

CONCLUSION

From the study, analysis and experimental, and theoretical results obtained, the 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 dynamic negative resistance (–R), frequency, and the resonance at peak frequency, is linear.

Acknowledgement

REFERENCES

[1] LEO ESAKI, "Discovery of the Tunnel Diode"; IEEE Trans. on Electron Devices, Vol. ED–23, No. 7, July 1976, pp. 644–647.

[2] T.M., KLAPWIJK, "Physics of tunneling Barriers", In: Supconducting Quantum Interference Devices and Their Applications Conf., Berlin, 1985, 0pp. 1–129.

[3] L.L., MOSKUITIN, "Amplitude Characteristics and Gain Stabliity of Tunnel Amplifiers", Telecommu. Radio Eng., Vol. 29–30, No. 4, April 1985, pp. 109–114.

[4] R.S., VIRK, "Using Tunnel Diode Technology", MSN Microw Syst. News Commu. Tech. (USA), Vol. 17, No. 12, Nov. 1987, pp. 68–75.

[5] V., STUPELMAN and G., FILARETOV, "Semiconductor Devices"; MIR Publisher, Moscow, 1976, pp. 93.

[6] V., GERASIMOV, O., KNYAZKOV, A., KRASNOPOLSKY and V., SUKHORUKOV, "Fundamentals of Industrial Electronics"; MIR Publisher, Moscow, 1980, pp. 23.

[7] V.A., BRUK, V.V., GARSHENIN, A.I. KURNOSOV "Semiconductor Technology", MIR Publisher, Moscow, 1979, pp. 52.

[8] B.G., STREETMAN, "Solid State Electronic Devices"; Prentice Hall Inc., England Cliffs, New Jersy, 1980, pp. 206.

[9] P.M., CHIRLIAN, "A Technique for Cascading Tunnel Diode Amplifier", Proc. IRE, Vol. 48, No. 6, 1960, pp. 1156.

[10] J., MILLMANS and C.C., HALKIAS, "Integrated Electronics; Analog and Digital Circuits and Systems", Mc. Graw Hill Book Comp., Japan, 1933.

[11] M.A., OMAR, "Elementary Solid - State Physics Principles and Applications, "Addison-Wesley Publ. Comp., U.S.A., 1975.

[12] P.M., CHIRLIAN, Proc. IRE; Vol. 49, No. 1, Jan. 1961, pp. 375.

[13] C.O., HARBOURT, Proc. IRE, Vol. 49, No. 1, 1961, pp. 373–374.

[14] N.F., MOODY, Proc. IRE, Vol. 49, part 2, No. 4, April, 1961, pp. 835.