SMALL-SIGNAL CHARACTERISTICS OF DIODE-STABILIZED LINEAR INTEGRATED DEVICES*

by

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ABSTRACT

Small-signal characteristics and frequency response of diode-stabilized linear integrated devices (circuits) are examined. The built-in feedback property is explained. It is found that the circuit provides low input impedance, high output impedance and small internal feedback. The frequency response of the circuit with the bias-diode is superior to that without the bias-diode. The current gain of the circuit can be controlled by appropriate design of active elements or passive elements. The experimental results using discrete components agree with the analysis.

I. INTRODUCTION

In the design of linear integrated circuits, one of the basic problems is the biasing of a common-emitter (CE) stage. The conventional biasing techniques used in discrete circuit design are not practical because of the requirement of a large emitter bypass capacitor. In order to overcome this difficulty, Widlar has developed a method using a diode-connected transistor to stabilize a CE stage.[1] A modified circuit (or device) is reported by Davis and Lin where a compound diode-transistor structure is used for temperature compensation.[2] In these papers, the stabilization aspect of the circuits is emphasized, but other characteristics of the circuits have not been treated. Since these circuits are designed for linear applications, one should consider both the stabilization properties and the small-signal characteristics such as input impedance, output impedance, internal feedback factor and the frequency response of the circuit.

The purpose of this work is to investigate the small-signal characteristics of the diode-stabilized CE circuit for linear integrated-circuit applications. It is found that the circuit is a very good current amplifier with low input impedance, high output impedance and low internal feedback factor. The frequency response of the circuit with the bias-diode is much better than that without the bias-diode. These improvements on device characteristics are obtained however with a sacrifice of the current gain. The experimental results using discrete components agree with the analysis.

II. THE FEEDBACK CONCEPT

The small-signal behavior of the diode-stabilized circuit does not seem to be predictable at the first glance because of the unconventional form of the diode-transistor connection. It is possible, however, to show that the circuit is actually a form of the current-shunt feedback amplifier. Based on the simple feedback concept one can predict the small-signal characteristics of the circuit. This method of analysis may provide better physical insight of the circuit operation and enable the designer to make further modification.

The circuit of Davis and Lin (Fig. 1) may be treated as a negative feedback circuit where the output current is sampled and is fed back to the input in shunt connection. Physically, the voltage V_{BE} has to be the same for the transistor Q_2 and the diode-connected transistor Q_1. As a result, the diode current I_1 is proportional to I_E of Q_2 and, thus, proportional to I_C of Q_2. The current I_1 can be taken as the feedback current and I_C of Q_2 can be taken as the output current. This current-shunt feedback connection stabilizes the current gain of the circuit.[3] The stabilization is achieved with a sacrifice of current gain. Furthermore, the diode-biased connection should reduce the input impedance and should increase the output impedance.

Mathematically, the feedback signal I_1 is related to the output current I_C by the following expression:

$$I_1 = I_E/K = I_C/h_{FB}K \tag{1}$$

where K is the ratio of the transistor emitter area to the diode emitter area and I_{CO} is assumed negligible. Therefore, the dc feedback factor is

$$\beta_{dc} = \frac{1}{h_{FB}K} = \frac{1 + h_{FE}}{K\ h_{FE}} \tag{2}$$

By making use of the general formula of a feedback amplifier, the overall current-gain A_{If} with feedback is

$$A_{If} = \frac{A_I}{1 + \beta A_I} = \frac{h_{FE}\ K}{1 + K + h_{FE}} \tag{3}$$

where $A_I = h_{FE}$ is used. The foregoing equation is identical to Eq. (4) of Davis and Lin. The variation of the current gain, due to the change of temperature or operating point, is greatly reduced because of the feedback action.

III. THE LOW-FREQUENCY SMALL-SIGNAL PARAMETERS

In the small-signal analysis, the following assumptions are made:

(1) Q_2 is made up of K transistors connected in parallel

(2) all transistors are identical

(3) the h-parameters of each transistor are h_{ie}, h_{re}, h_{fe} and h_{oe}.

(4) $1/h_{oe}$ is large compared to h_{ie}, and h_{re} of Q_1 is negligible.

From these assumptions, the h-parameters of Q_2 become h_{ie}/K, h_{re}, h_{fe} and $K\ h_{oe}$. The equations describing the basic amplifier Q_2 are, therefore,

$$V_i = \frac{h_{ie}}{K} I_{b2} + h_{re} V_o \tag{4}$$

$$I_o = h_{fe} I_{b2} + K\ h_{oe} V_o \tag{5}$$

If the feedback concept is used, Q_2 may be considered as the basic amplifier and Q_1 as the feedback network. The small-signal equivalent circuit is shown in Fig. 2. The overall h-parameters h_i, h_r, h_f and h_o are found by making use of Fig. 2:

A. Input Impedance (h_i): The input impedance of the circuit is the parallel combination of the impedances looking into the diode Q_1 (h_{id}) and the base of the transistor Q_2 (h_{it}). These impedances are given by:

$$h_{id} = \frac{V_i}{I_1} = \frac{V_i}{(1 + h_{fe})\, I_{b1}} = \frac{h_{ie}}{1 + h_{fe}} \tag{6}$$

$$h_{it} = h_{ie}/K \tag{7}$$

Therefore, the input impedance becomes

$$h_i = \frac{h_{id}\, h_{it}}{h_{id} + h_{it}} = \frac{h_{ie}}{1 + K + h_{fe}} \tag{8}$$

Alternatively, the input impedance can be obtained by using the feedback method. Thus,

$$h_i = Z_{if} = \frac{Z_i}{1 + \beta A_I} = \frac{h_{ie}}{1 + K + h_{fe}} \tag{9}$$

where $\beta = (1 + h_{fe})/K\, h_{fe}$ and $Z_i = h_{ie}/K$ are used. The input impedance can be made very small by choosing a large h_{fe}.

B. Forward Current-Transfer Ratio (h_f): The expression for the forward current-transfer ratio can be derived by using the feedback method.

$$h_f = \frac{h_{fe}\, K}{1 + K + h_{fe}} \tag{10}$$

C. Voltage Feedback Ratio (h_r): The voltage feedback ratio can be calculated by solving Eq. (4) and making use of the relation of $V_i/I_{b2} = - h_{id}$. The resultant expression is

$$h_r = \frac{V_i}{V_o} = \frac{h_{re}\ K}{1 + K + h_{fe}} \tag{11}$$

D. Output Impedance (h_o): Equation (5) may be rewritten as

$$1 = h_{fe}\frac{I_{b2}}{I_o} + h_{oe}\frac{V_o}{I_o} \tag{12}$$

Since $I_{b2} = - I_1$, one obtains

$$\frac{I_{b2}}{I_o} = - \frac{I_1}{I_o} = - \frac{1 + h_{fe}}{K\ h_{fe}} \tag{13}$$

By substituting Eq. (13) into Eq. (12), the following expression is obtained:

$$h_o = \frac{I_o}{V_o} = \frac{h_{oe}\ K}{1 + K + h_{fe}} \tag{14}$$

This result can also be obtained by using the negative feedback concept.

With the foregoing results, expressions including the effects of the source and load impedance can be obtained easily.

IV. FREQUENCY RESPONSE

The frequency response of the functional block is of primary importance since the functional block is the basic component of a linear amplifier. An equivalent circuit using the hybrid-π model (Fig. 3) may be used for the calculation of the 3-db frequency of the short-circuited current gain. From the negative feedback concept, one may expect a higher 3-db frequency for the stabilized circuit.

To simplify the derivation, it is assumed that $C_e \gg C_c$, $R_L = 0$. Furthermore, the following equivalent representations are used:

$$Z_1 = \frac{r_{bb'}}{1 + j\omega\, C_c\, r_{bb'}} + \frac{r_{b'e}}{1 + j\omega\, C_e\, r_{b'e}} = Z_{bb'} + Z_e \tag{15}$$

$$Z_2 = \frac{r_{bb'}}{K} + \frac{r_{b'e}/K}{1 + j\omega\, C_e\, r_{b'e}} \tag{16}$$

The following equations can be obtained from Fig. 3:

$$I_1 = I_2 + I_3 + I_4 \tag{17}$$

$$I_2 Z_1 = I_4 Z_2 \tag{18}$$

$$I_3 = \frac{g_m\, r_{b'e}\, I_2}{1 + j\omega\, C_e\, r_{b'e}} = g_m\, Z_e\, I_2 \tag{19}$$

$$I_o = -\, g_m\, K\, V_{b'e2} = -\, g_m\, Z_e\, I_4 \tag{20}$$

By solving Eqs. (17) through (20), one obtains

$$\frac{I_o}{I_i} = \frac{-\, g_m\, Z_e(Z_1/Z_2)}{1 + g_m\, Z_e + Z_1/Z_2} \tag{21}$$

The ratio Z_1/Z_2 turns out to be K if the effect of C_c is negligible. As a result, Eq. (21) becomes

$$\frac{I_o}{I_i} = \frac{-\, g_m\, Z_e\, K}{1 + K + g_m\, Z_e} = \frac{K\, h_{fe}/(1 + K + h_{fe})}{1 + jf(1 + K)/f_\beta(1 + K + h_{fe})} \tag{22}$$

where f_β is the cutoff frequency of the CE stage without the biasing diode. The cutoff frequency with the biasing diode becomes

$$f'_\beta = f_\beta(1 + K + h_{fe})/(1 + K) \tag{23}$$

A better frequency response is realized for the stabilized CE stage. This result is not obvious if one does not treat the circuit from the feedback viewpoint.

If $R_L \neq 0$, the effect of C_c cannot be ignored. By using Miller's theorem to account for C_c, the following expression for the current gain can be obtained:

$$\frac{I_o}{I_i} = \frac{-\, g_m\, K'\, Z'_e}{1 + K' + g_m\, Z_e} \tag{24}$$

where

$$Z'_e = r_{b'e}/(1 + j\omega\ C\ r_{b'e})$$

$$C = [C_e + C_c(1 + g_m\ K\ R_L)]$$

$$K' = (Z_{bb'} + Z_e)K/(r_{bb'} + Z'_e)$$

By making use of Eq. (24) and the typical values of a silicon transistor, the frequency response of the diode-stabilized circuit is calculated and plotted in Fig. 4 for $R_L = 0$ and $R_L = 100\Omega$. The hybrid-π parameters used in the numerical calculation are $r_{bb'} = 250\Omega$, $r_{b'e} = 3k$, $C_e = 100$ pF, $C_c = 5$ pF, $K = 3$ and $h_{fe} = 120$. The cutoff frequencies f_β and f'_β are 500 kHz and 15.5 mHz respectively.

V. CONTROL OF K BY PASSIVE ELEMENTS

The feedback factor β in the Davis-Lin circuit is controlled by the area ratio of active devices. It is also possible to control β by passive elements. Figure 5 shows a circuit using resistors to control the feedback factor. This circuit is similar to Widlar's circuit where Q_1 and Q_2 are identical. If the h-parameters are assumed to be independent of the operating point, the current-voltage relationship may be expressed as follows:

$$V_1 = I_1 \left[\frac{R_1 + h_{ie}}{1 + h_{fe}} + R_3 \right] = I_e \left[\frac{R_2 + h_{ie}}{1 + h_{fe}} + R_4 \right] \tag{25}$$

Therefore, the proportional factor K is

$$K = \frac{I_e}{I_1} = \frac{R_1 + h_{ie} + R_3(1 + h_{fe})}{R_2 + h_{ie} + R_4(1 + h_{fe})} \tag{26}$$

If the transistors' current gains are reasonably high, we may assume that $(R_1 + h_{ie}) \ll R_3(1 + h_{fe})$ and $(R_2 + h_{ie}) \ll R_4(1 + h_{fe})$. As a result, Eq. (26) becomes:

$$K \approx \frac{R_3}{R_4} \tag{27}$$

Thus, the overall gain of the amplifier becomes

$$A_i \approx K \approx \frac{R_3}{R_4} \tag{28}$$

if h_{fe} is very large.

It should be pointed out that the method of using passive elements to control the feedback factor is not necessarily better than the Davis-Lin device. The merits of the two methods depend on the requirements of process steps, isolation islands and device areas. If the variation of current gain with emitter current is important, the Davis-Lin circuit has a definite advantage because its K is independent of the operating current. The circuit using different emitter resistors does not provide the same current for the diode and the transistor. Thus, $h_{fe1} \neq h_{fe2}$ and K would not be a constant.

VI. EXPERIMENTAL RESULTS

Experiments were performed using discrete silicon devices (Motorola MD2219 and TI 2N2641). Four transistors are connected together to form the transistor Q_2 and a fifth transistor is used as the biasing diode Q_1. Thus the value of K is 4. It was not possible to select five transistors with all h-parameters exactly matched. Therefore, the average values of the h-parameters of individual devices were used for the calculation of the h-parameters of the composite device. In these calculations, Eqs. (8), (10), (11) and (14) were employed, and the results are shown in the following table:

	A Single Transistor (Measured)	The Stabilized Composite Device	
		Calculated	Measured
h_{fe}	108	3.82	3.5
h_{oe}	12 µmho	0.43 µmho	1 µmho
h_{ie}	3600 ohm	32 ohm	30 ohm
h_{re}	1.5×10^{-4}	5.3×10^{-6}	9×10^{-6}

The measured and calculated results are close despite the unmatched parameters and the current-hogging effect. In a device such as the Davis-Lin circuit, the correlation between the calculated and measured results should be better.

The frequency response of Q_2 and the composite circuit (K=3) was measured. The cutoff frequency for Q_2 alone was 350 kHz when R_L = 100 ohm was used. The cutoff frequency for the composite circuit was over 10 mHz. Unfortunately, quantitative comparison between the theory and experiment was not possible when discrete devices were used, because of the spread of hybrid-π parameters, the extrinsic elements and current hogging. However, the experimental results are in agreement with the theory (Fig. 4) qualitatively. Further study of the frequency response using the Davis-Lin device is desirable.

VII. CONCLUSION

An analysis of the diode-stabilized linear integrated circuit has been made based on the simple feedback concept. The small-signal parameters were derived to demonstrate the effects of the diode connected transistor. It has been shown that the circuit has low input impedance, high output impedance and low internal feedback factor. The cutoff frequency of the diode-stabilized circuit is approximately $h_{fe}/(1 + K)$ times the cutoff frequency of the CE stage without the biasing diode. The advantages, however, are achieved with a sacrifice of the current gain. Finally, it was demonstrated that passive elements could be used to control the characteristics of the circuit. Thus, the external characteristics of the circuit can be modified by either active or passive elements or both. The results of the small-signal analyses were confirmed by experiments using discrete components.

In principle, the diode-stabilized CE stage is not better than any feedback amplifier. The feedback factor of the stabilized circuit is frequency dependent when stray elements (such as overlap-diode capacitance) are taken into account. The analysis is further complicated if mismatched components are used.[4] In practical applications, however, this circuit is simpler than any other existing circuits. Furthermore, it takes advantage of the desirable features of integrated circuits such as close matching and thermal coupling of active and temperature sensitive components.

REFERENCES

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FIGURE CAPTIONS

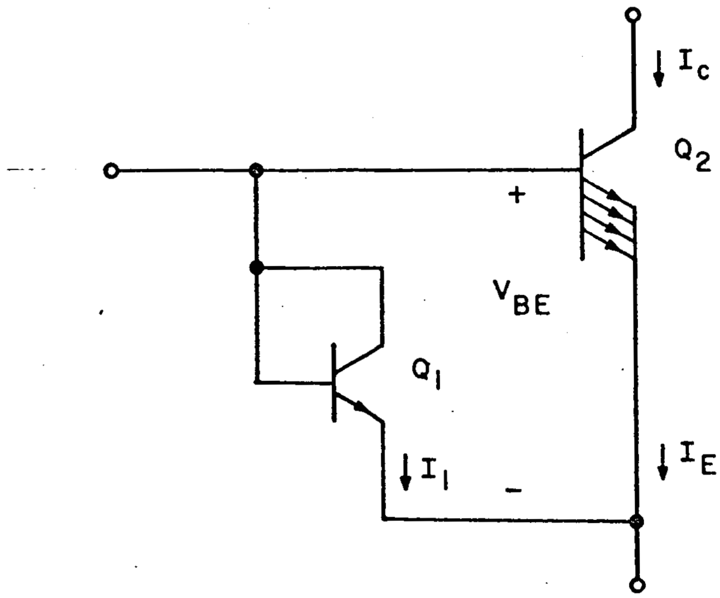
Fig. 1 - The Davis-Lin Device

Fig. 2 - The Small-Signal Equivalent Circuit of Fig. 1

Fig. 3 - The Hybrid-π Model

Fig. 4 - The Frequency Response of the Diode-Stabilized Circuit

Fig. 5 - A Stabilized Circuit with Passive Elements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Q 2
+
V BE
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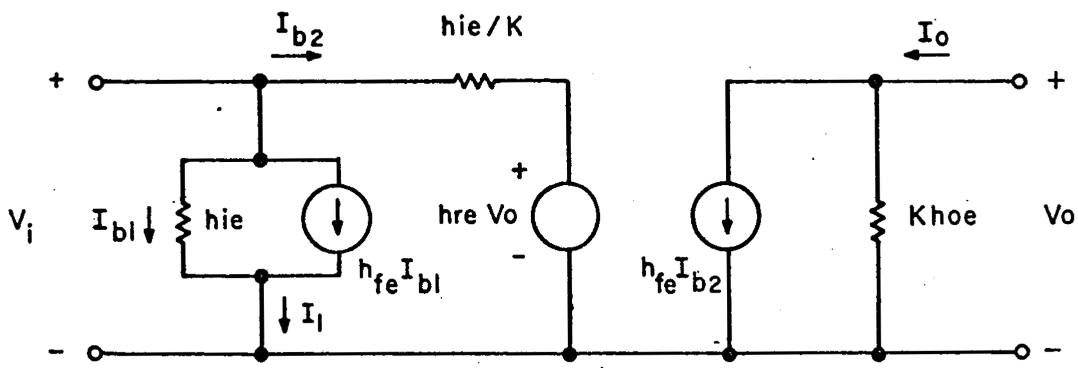
I E
−

FIG. 1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hie / K
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I 1
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FIG. 2

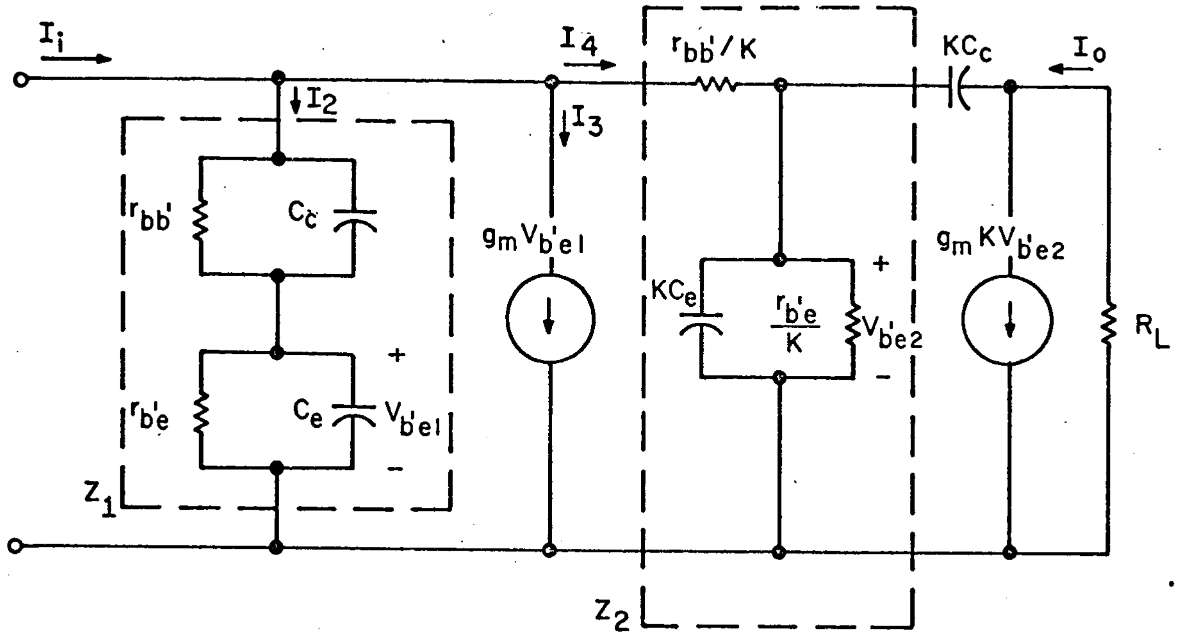

FIG. 3

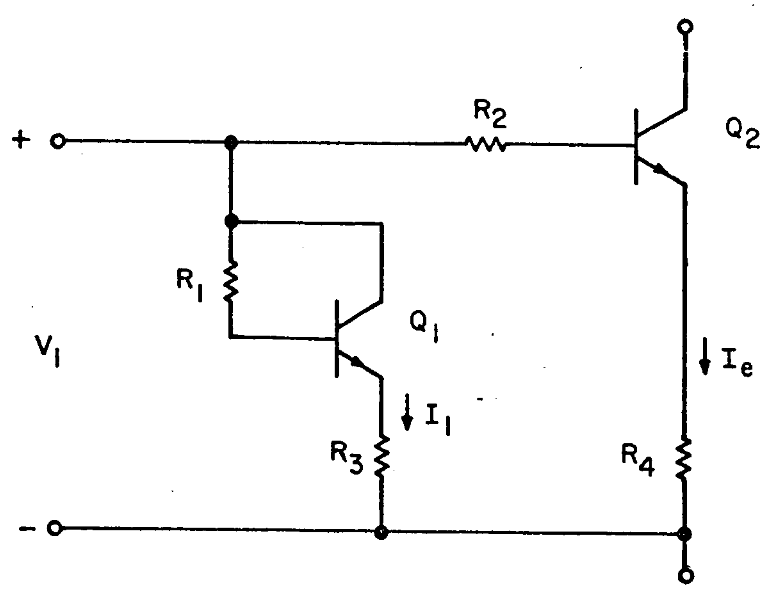

FIG. 5

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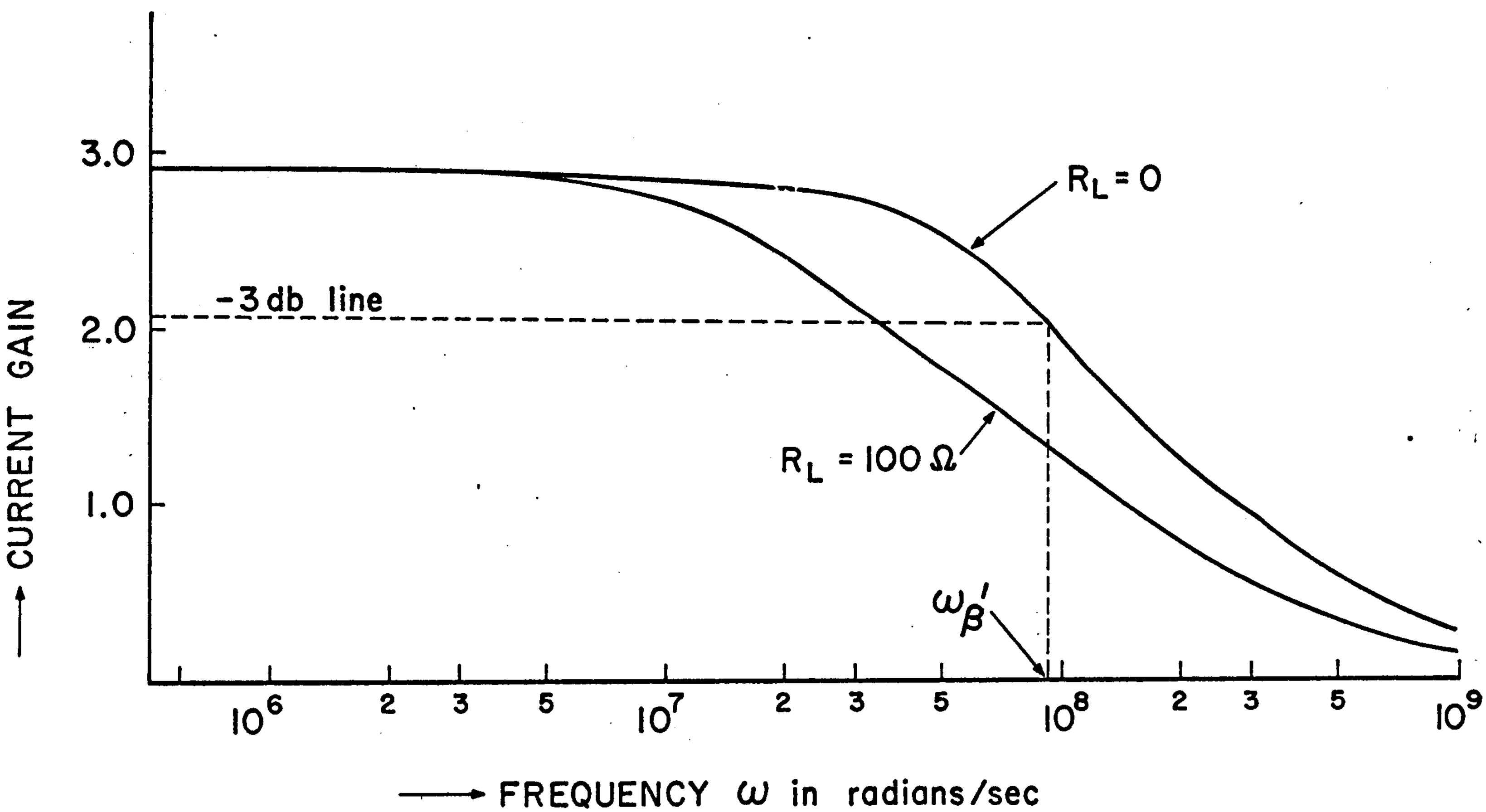

FIG. 4