

# A SIGNAL-DIFFERENCING WIDE-FREQUENCY CURRENT-TUNABLE PHASE SHIFTER

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## ABSTRACT

A new integrable fully-balanced wide-frequency current-tunable phase shifter is presented using a signal-differencing technique. The architecture of the circuit is relatively simple and symmetry with differential signals. The corner frequency is linearly tunable, through a bias current, over a wide-frequency sweep range of approximately three orders of magnitude. The maximum useful corner frequency is in excess of 112 MHz.

## I. INTRODUCTION

Phase shifters are utilised in many applications such as in a sinusoidal quadrature oscillator used in digital modulators of an integrated receiver. It is usually desirable that the architecture of such devices is fully balanced with differential signals so as to enable, for example, accurate quadrature outputs with maximum symmetry over a wide tunable-frequency sweep range. There are other significant, well understood advantages in employing a fully balanced realisation [1].

Several techniques of phase shifters have been suggested [2-3].

In this paper, an integrable fully-balanced wide-frequency current-tunable phase shifter is presented using a signal-differencing technique. The architecture of the circuit is relatively simple and symmetry with differential signals. The corner frequency of the phase shifter is linearly current-tunable using a tunable  $r_e$  network where  $r_e$  is the small-signal dynamic resistance of a forward biased base-emitter junction of a bipolar transistor.

## II. CIRCUIT DESCRIPTIONS

Figure 1 shows the basic circuit configuration of the signal-differencing current-tunable phase shifter consisting of ten matched npn transistors Q1 to Q10, a capacitor C and two current sinks  $I_1$  and  $I_f$ . The differential, small-signal, input voltage  $V_{in}$  is applied to the bases of two differential pairs Q1-Q2 and Q3-Q4, between points A and B, and the resulting differential, small-signal, output voltage  $V_o$  is taken across the emitters of Q9 and Q10, between points G and F. The corner frequency  $\omega_o$  of the phase shifter, typically defined at the point where the magnitude and the phase shift of its transfer function  $V_o/V_{in}$  become 0 dB and -90 degrees, respectively, is tunable using a current-tunable loading resistance  $R = 4r_e$ , formed by Q5, Q6, Q7 and Q8.

The two current sinks  $I_1$  and  $I_f$  may be implemented through the conventional Wilson current mirrors. Current  $I_1 / 2$  biases the (Q3, Q9) and the (Q4, Q10) branches, whilst a frequency setting current  $I_f / 2$  biases the (Q1, Q8, Q7) and the (Q2, Q5 and Q6) branches. It can be seen from Figure 1 that the architecture of the circuit is symmetry and hence the name "fully-balanced" phase shifter. The circuit is also relatively simple and is "integrable" as all active devices can be fabricated on-chip.

## III. IDEAL ANALYSIS

Referring to Figure 1, assuming that the bases of Q9 and Q10 at points D' and E' are temporarily disconnected with points D and E,

and as a result the bases of Q9 and Q10 at D' and E' are then temporarily connected together with an appropriate bias voltage say  $V_{bias}$ . In such a temporary case, let the resulting differential, small-signal, output voltage across points D and E be  $V_{o1}$  and that across points F and G be  $V_{o2}$ . The differential, small-signal, input voltage  $V_{in}$  results in a differential output current  $i_{d1}$  through the loading impedance  $Z_1$  between points D and E where

$$Z_1 = \frac{R}{(1 + s\tau)} \quad (1)$$

$$\tau = CR = \left( \frac{8CV_T}{I_f} \right) \quad (2)$$

$V_T$  is the usual thermal voltage associated with a pn junction and is approximately equal to 25 mV at room temperature. The 1st-order transfer function  $V_{o1} / V_{in}$  therefore represents a low-pass filter of the form

$$\frac{V_{o1}}{V_{in}} = \frac{2}{(1 + s\tau)} \quad (3)$$

In addition,  $V_{in}$  also results in a differential output current  $i_{d2}$  through the loading impedance  $Z_2$  between points F and G where

$$Z_2 = 4 \frac{V_T}{I_1} \quad (4)$$

The transfer function  $V_{o2}/V_{in}$  therefore represents a buffer of the form

$$\frac{V_{o2}}{V_{in}} = 1 \quad (5)$$

By reconnecting the bases of Q9 and Q10 with points D and E (as shown in Figure 1),

the resulting differential, small-signal, output voltage  $V_o$ , taken across points G and F, is obtained through superposition, i.e.  $V_o = V_{o1} - V_{o2}$ , and hence the name “signal-differencing”. Consequently, the transfer function,  $V_o/V_{in}$  is of the form

$$\frac{V_o}{V_{in}} = \frac{1 - s\tau}{1 + s\tau} \quad (6)$$

It can be seen that equation (6) represents the transfer function of a phase shifter. The corner frequency  $\omega_o$  of such a filter is of the form

$$\omega_o = \frac{1}{\tau} = \frac{I_f}{8CV_T} \quad (7)$$

It can be seen from equation (7) that the corner frequency  $\omega_o$  is tunable through the bias current  $I_f$  and hence the name “current-tunable phase shifter”.

#### IV. SIMULATION RESULTS

The performance of the circuit shown in Figure 1 has been simulated using a circuit simulator package ViewSpice [4], running on a 32-bit personal computer. The npn transistors are modeled by QMPS2222A, whose transition frequency  $f_T$  is at 300 MHz [4]. Figure 2 illustrates magnitude (dB) and phase shift (degree) of  $V_o / V_{in}$  versus frequency (Hz) obtained from the simulation using, as an example, capacitor  $C = 0.01 \mu\text{F}$ ,  $(I_f/2) = 100 \mu\text{A}$ ,  $(I_f/2) = 70 \mu\text{A}$ ,  $0.7 \text{ mA}$  and  $7 \text{ mA}$ . It can be seen from Figure 2 that, for the phase shift at -90 degrees, the corresponding corner frequencies  $\omega_o$  for individual values of  $(I_f/2)$

are at 10.5 kHz, 106.6 kHz and 1.06 MHz, respectively, with the corresponding magnitude of approximately 0 dB.

Figure 3 depicts the simulation results of both the corner frequencies (Hz) and the corresponding magnitude (dB) of  $V_o/V_{in}$ , for the phase shift at -90 degrees, versus the bias current  $I_f/2$ , using a fixed capacitor  $C = 0.01 \mu\text{F}$  and  $I_1/2 = 100 \mu\text{A}$ . For purposes of comparison, the expected (ideal) results are also included. It can be seen from Figure 3 that both the expected and the simulated results are consistent, and the corner frequency is linearly current-tunable over a “wide-frequency” sweep range of approximately 3 orders of magnitude.

Figure 4 shows the simulation results of both the corner frequencies (Hz) and the corresponding magnitude (dB) of  $V_o/V_{in}$ , for the phase shift at -90 degrees, versus the capacitance  $C$ , using a fixed bias current  $I_f/2 = 2 \text{ mA}$  and  $I_1/2 = 100 \mu\text{A}$ . For purposes of comparison, the expected (ideal) results are also included. It can also be seen from Figure 4 that both the expected and the simulated results are linear and consistent and, by using a minimum frequency setting capacitance of 20 pF, the upper frequency limit can be expected to be 112 MHz.

#### V. DISCUSSION AND CONCLUSIONS

A new integrable signal-differencing wide-frequency current-tunable phase shifter has been presented. The architecture of the circuit is symmetry with differential signals.

The circuit is also relatively simple and integrable on-chip. Both the simulated and the expected results are consistent. The corner frequency is linearly current-tunable over a wide-frequency sweep range of approximately three orders of magnitude. The maximum useful corner frequency is around 112 MHz. By using better transistors of much higher  $f_T$  (e.g. in the region of several GHz) and much smaller value of C (e.g. using stray capacitance), much higher, more useful, values of the corner frequency, as suggested by equation (7), could be expected.

#### ACKNOWLEDGEMENTS

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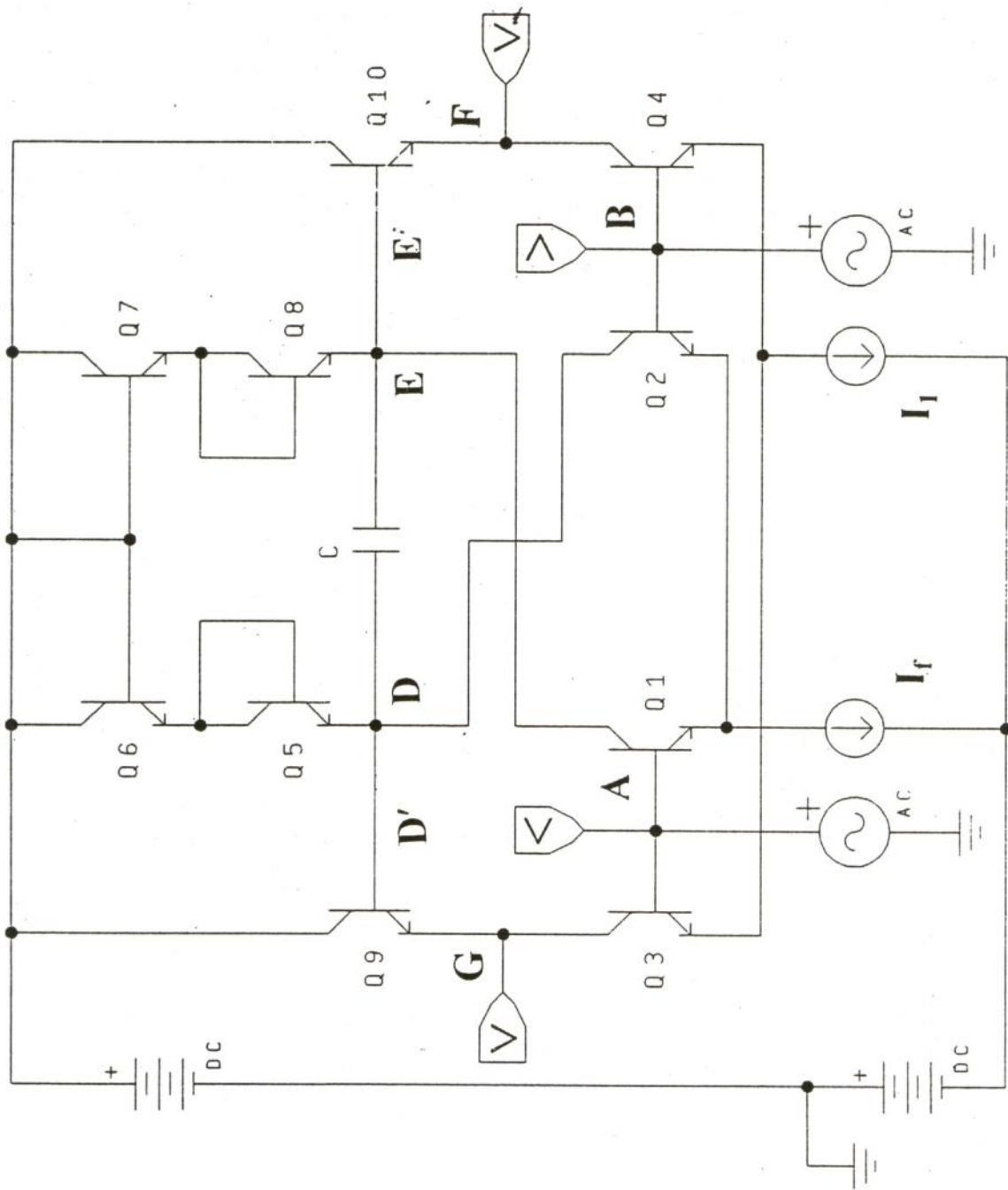


Figure 1 Schematic diagram of the signal-differencing wide-frequency current-tunable phase shifter

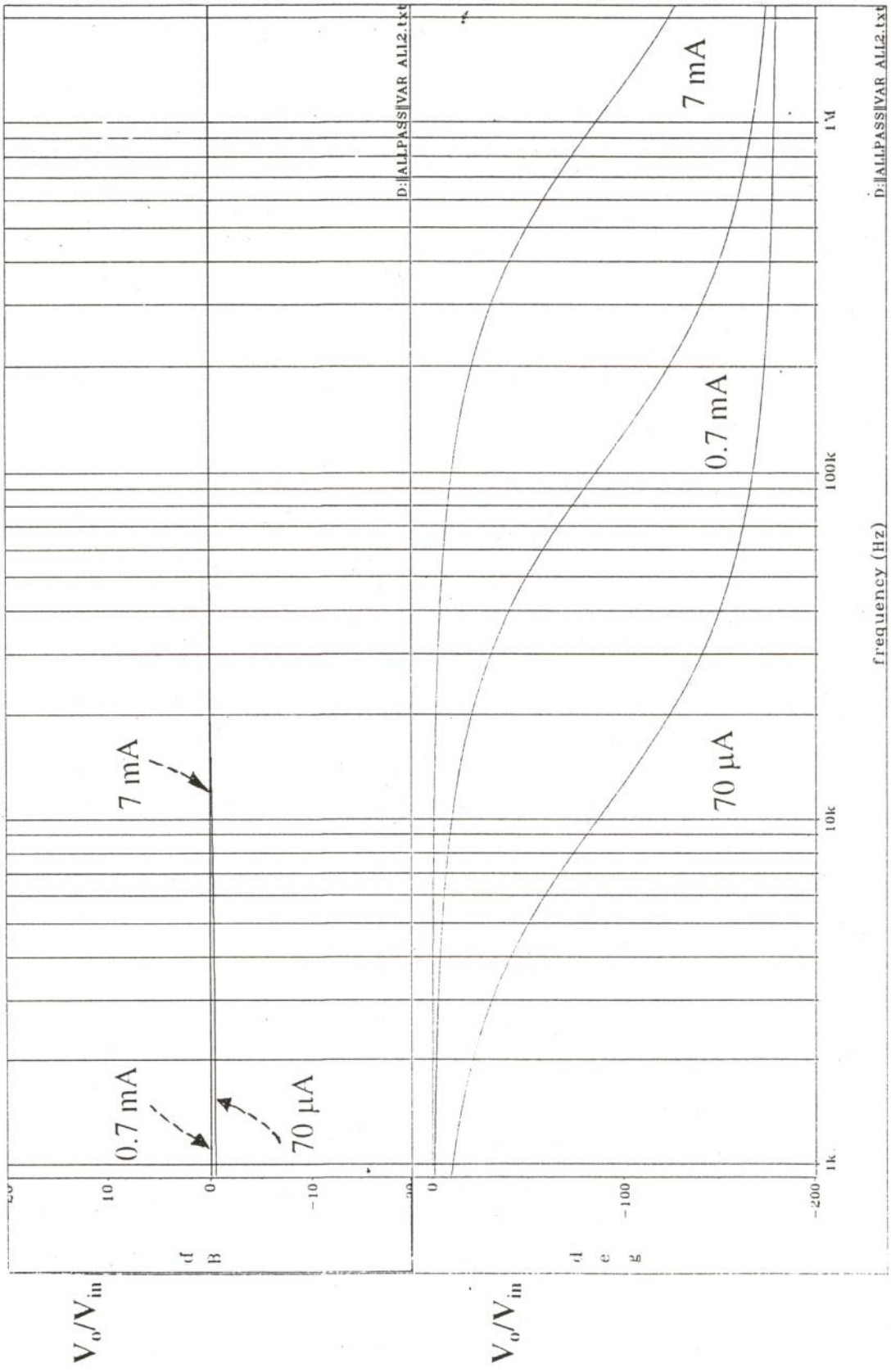


Figure 2 Magnitude (dB) and phase shift (degree) of  $V_o/V_{in}$  versus frequency (Hz) using the capacitor  $C = 0.01 \mu F$ ,  $I_1/2 = 100 \mu A$  and  $I_1/2 = 70 \mu A$ ,  $0.7 mA$  and  $7 mA$

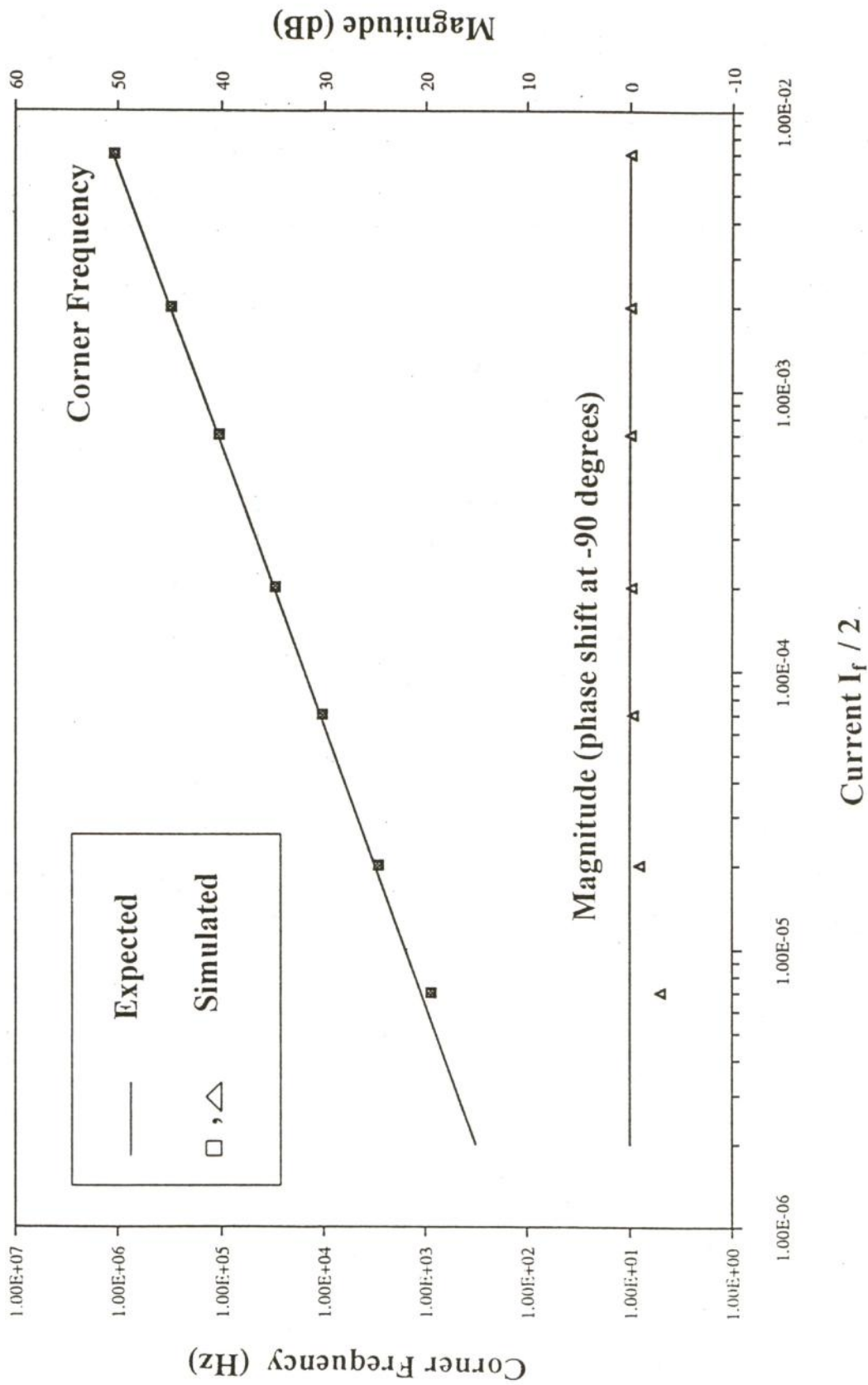


Figure 3 Corner frequencies (Hz) and the corresponding magnitude (dB) of  $V_o/V_{in}$ , for the phase shift at -90 degrees, versus the bias current  $I_r/2$  (A), using a fixed capacitance  $C = 0.01 \mu\text{F}$  and  $I_r/2 = 100 \mu\text{A}$

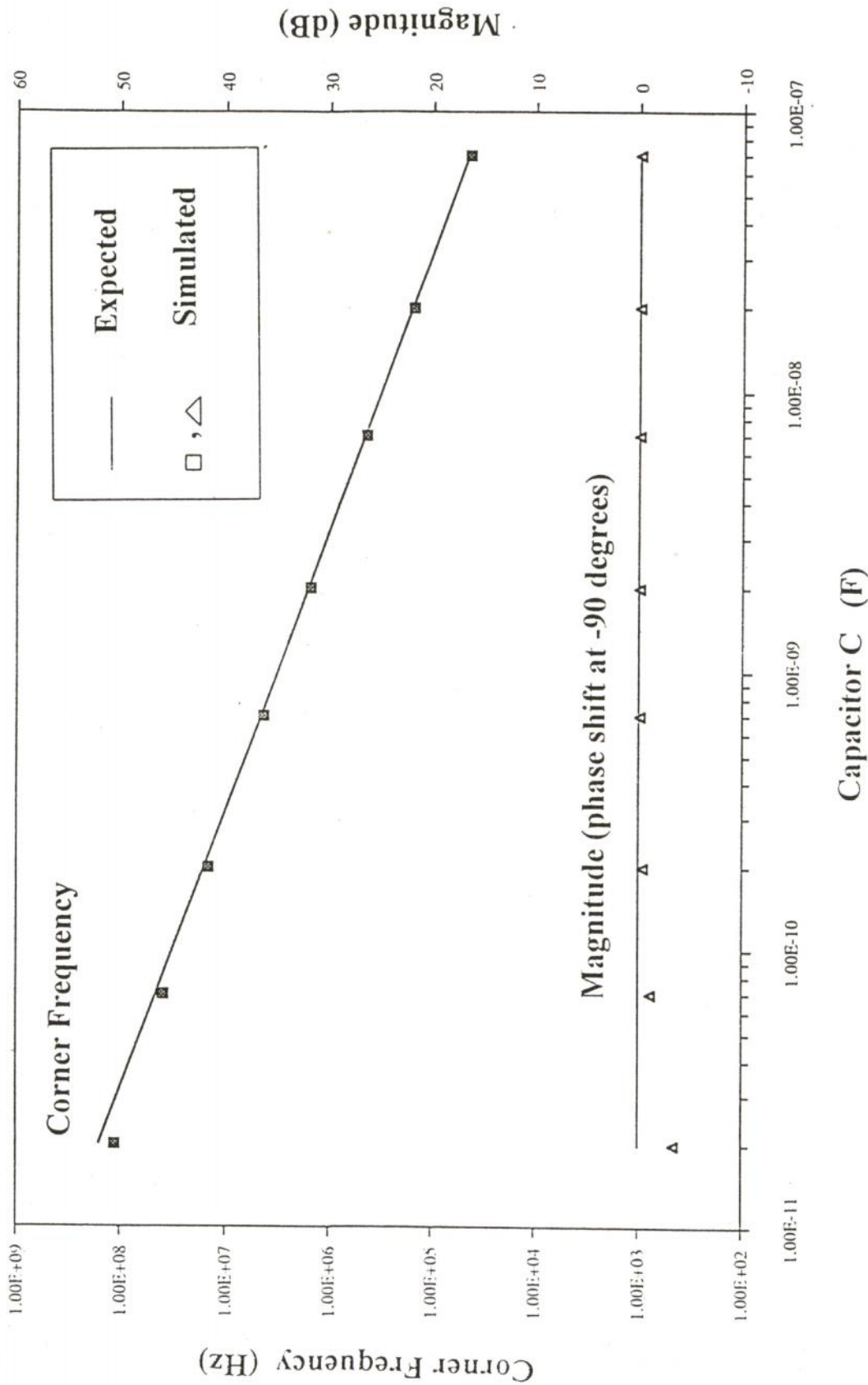


Figure 4 Corner frequencies (Hz) and the corresponding magnitude (dB) for  $V_o/V_{in}$  for the phase shift at -90 degrees, versus the capacitance C (F), using a fixed bias current  $I_{D/2} = 2\text{mA}$  and  $I_{I/2} = 100\ \mu\text{A}$