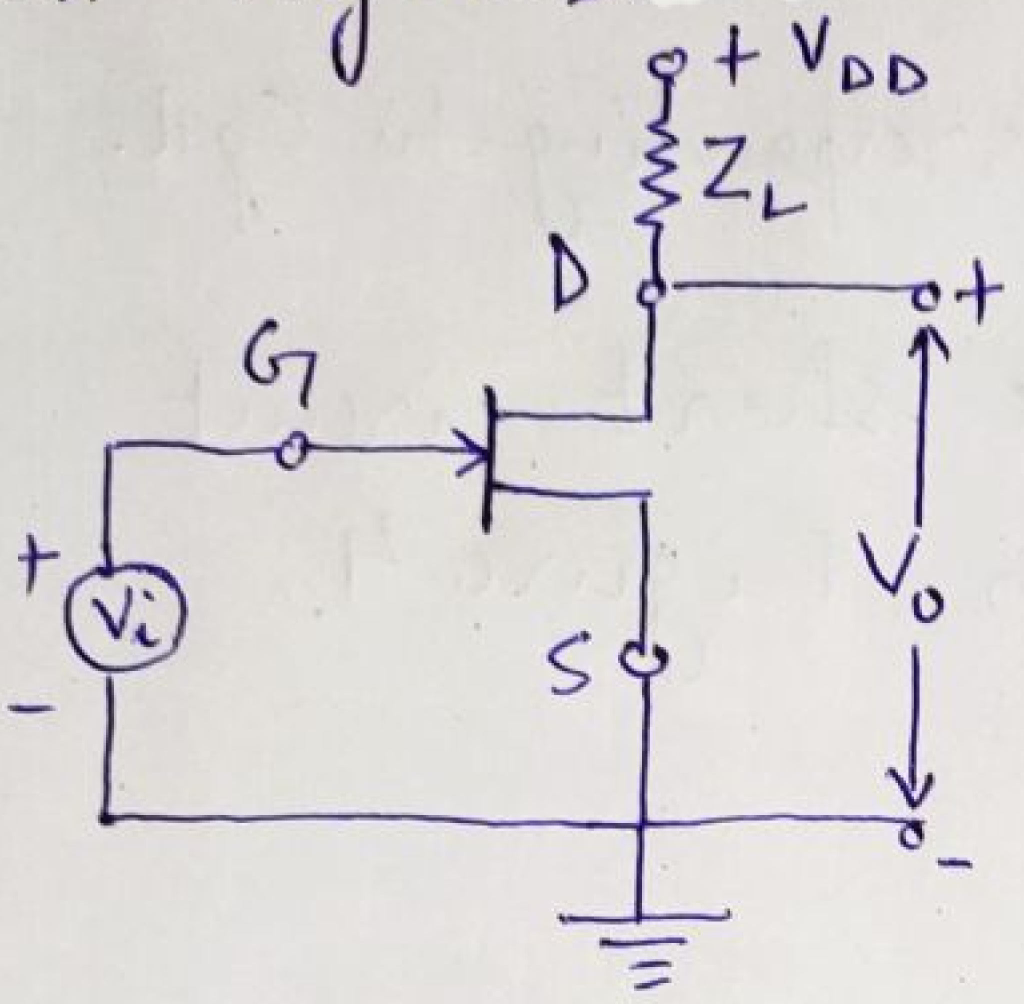
The Common Source (CS) FET Amplifier at High Frequencies (1)

The Figure 1 shows the circuit of CS amplifier. The equivalent circuit at high frequencies is shown in Figure 2.



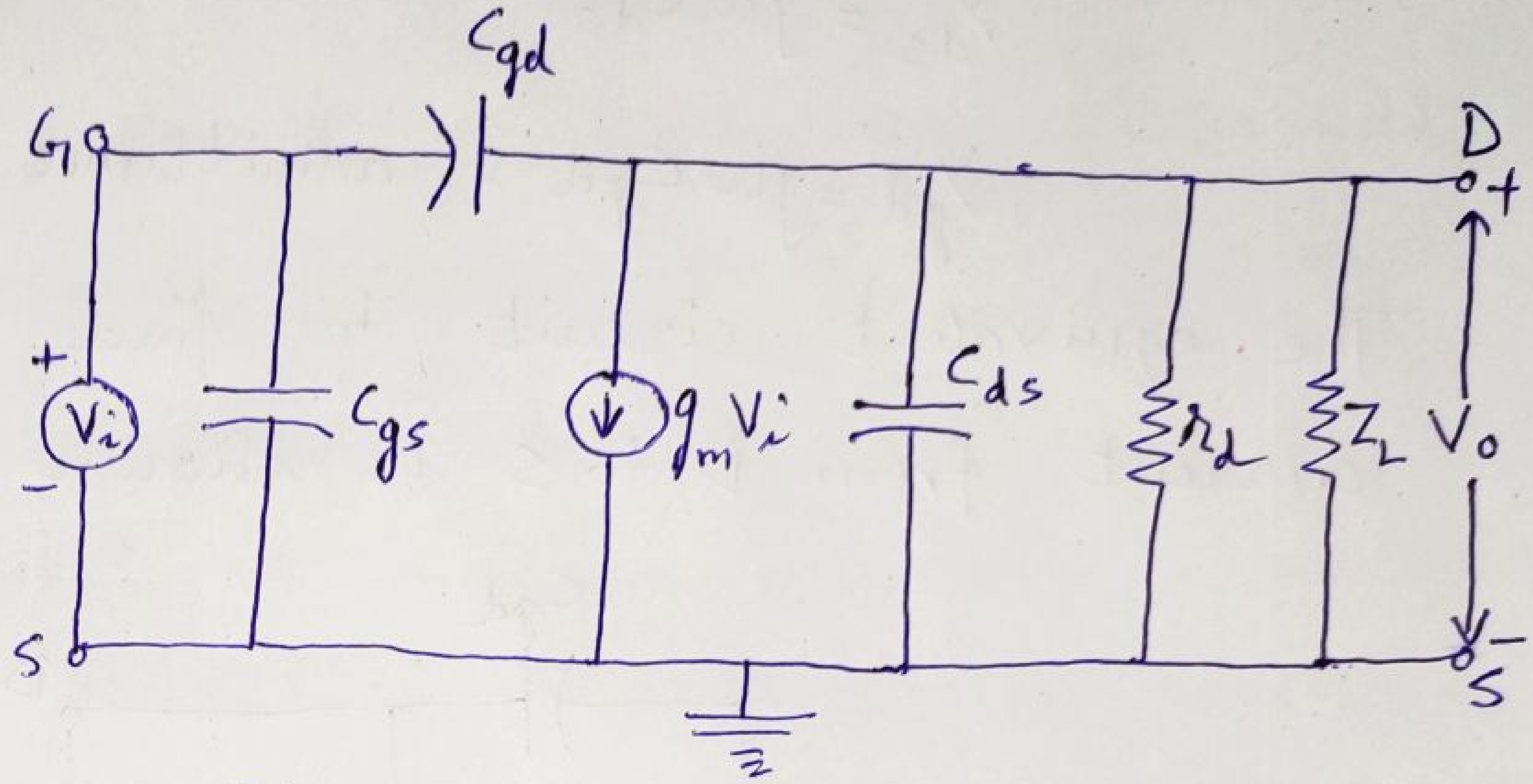


Figure 1. Figure 2.

The Norton's equivalent circuit between D and S is obtained by finding the short-circuit current from D to S and impedance Z seen from output point with independent voltage sources short circuited and independent current sources open-circuited. With $V_i = 0$, current $g_m V_i = 0$, the circuit of Figure 2 reduces to circuit of Figure 3.

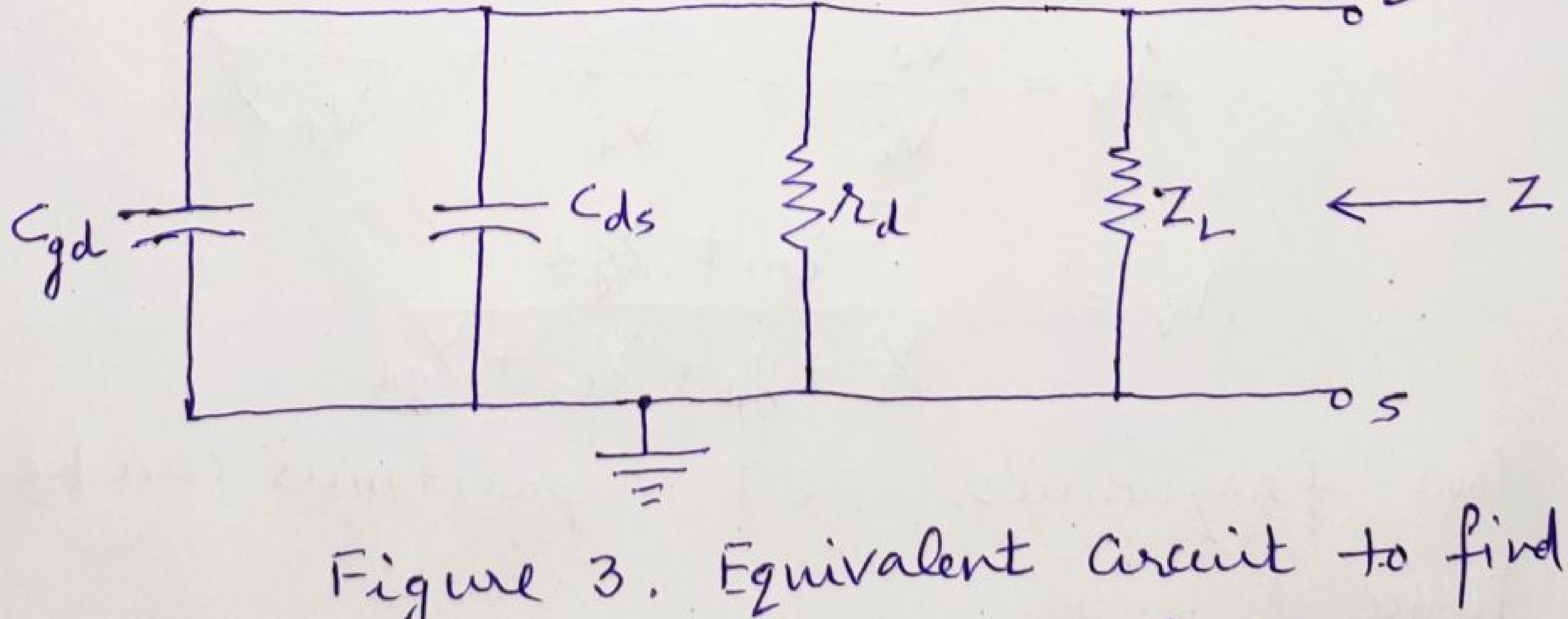


Figure 3. Equivalent circuit to find Z.

Hence, admittance at the output point

$$Y = \frac{1}{Z} = Y_L + g_d + Y_{ds} + Y_{gd}$$

where $Y_L = \frac{1}{Z_L}$ is admittance corresponding to Z_L.

$g_d = \frac{1}{r_d}$ is conductance corresponding to r_d.

$Y_{ds} = j\omega C_{ds}$ is admittance corresponding to C_{ds}

$Y_{gd} = j\omega C_{gd}$ is admittance corresponding to C_{gd}.

The equivalent circuit to find the short circuit current from D to S is shown in Figure 4.

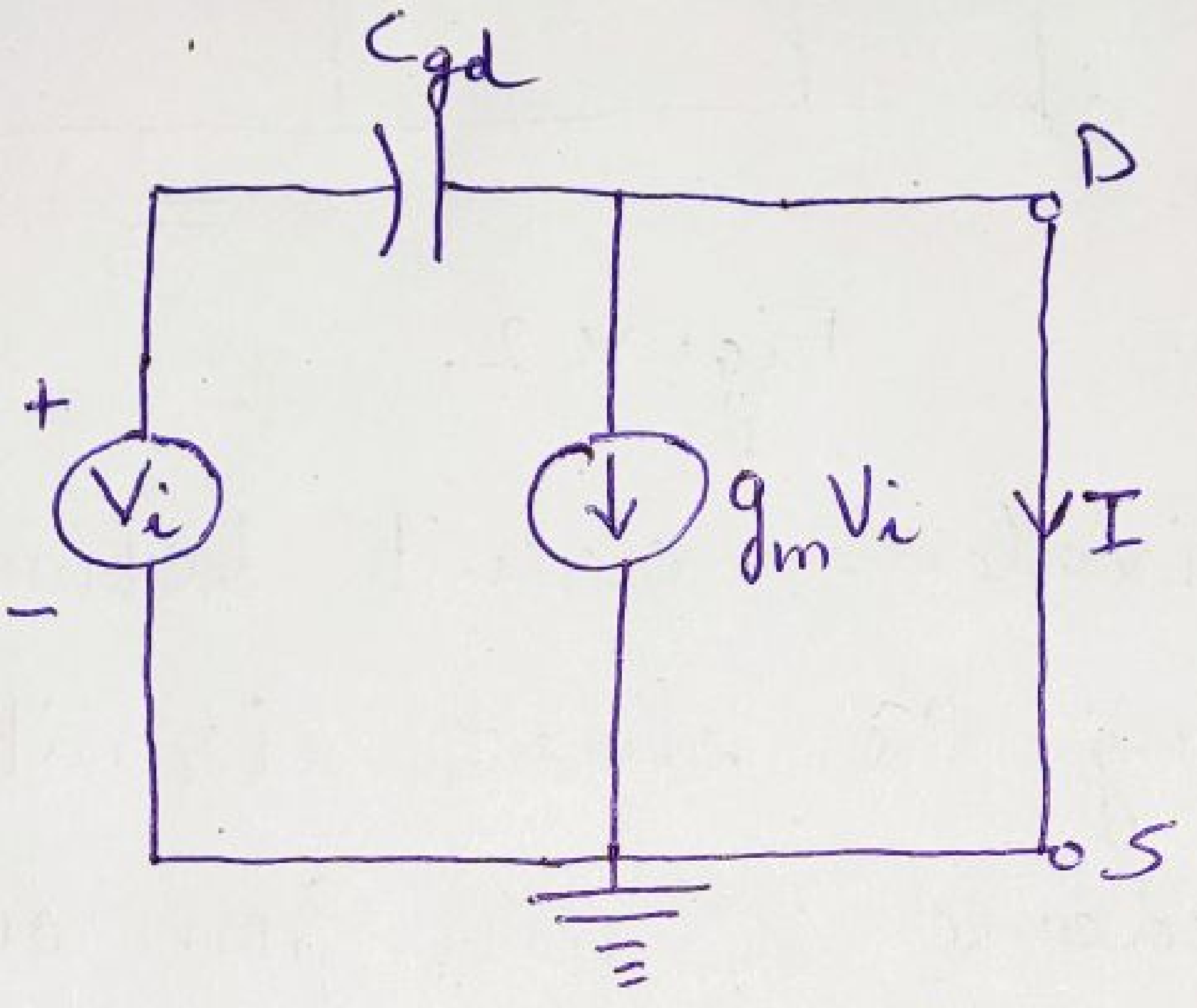


Figure 4. Equivalent circuit to find I.

Hence, $I = -g_m V_i + V_i Y_{gd}$

<u>Voltage Gain</u>: Voltage gain A_V with load Z_L included is given by

$$A_V = \frac{V_o}{V_i} = \frac{IZ}{V_i} = \frac{I}{V_i Y}$$

$$\therefore \quad A_V = \frac{-g_m + Y_{gd}}{Y_L + g_d + Y_{ds} + Y_{gd}}$$

At low frequencies, FET capacitances can be neglected and hence

$$Y_{ds} = Y_{gd} = 0$$

Therefore at low frequencies,

$$A_V = \frac{-g_m}{Y_L + g_d} = \frac{-g_m}{(1/Z_L) + (1/r_d)}$$

$$A_V = \frac{-g_m r_d Z_L}{r_d + Z_L} = -g_m Z_L'$$

where $Z' = Z_L \parallel r_d$

Input Admittance

From Figure 2, it is found that the gate circuit is not isolated from the drain circuit, but connected by C_{gd}.

According to Miller's theorem, an impedance Z' connected between two points (1) and (2) of a circuit can be replaced by $Z_1 = \frac{Z'}{1-A_V}$ from (1) to ground and $Z_2 = \frac{Z' A_V}{A_V - 1}$ from (2) to ground, where A_V is the voltage gain $\frac{V_2}{V_1}$.

Applying Miller's theorem to the circuit of Figure 2, the circuit of Figure 5 is obtained, where capacitances are replaced by equivalent admittances.

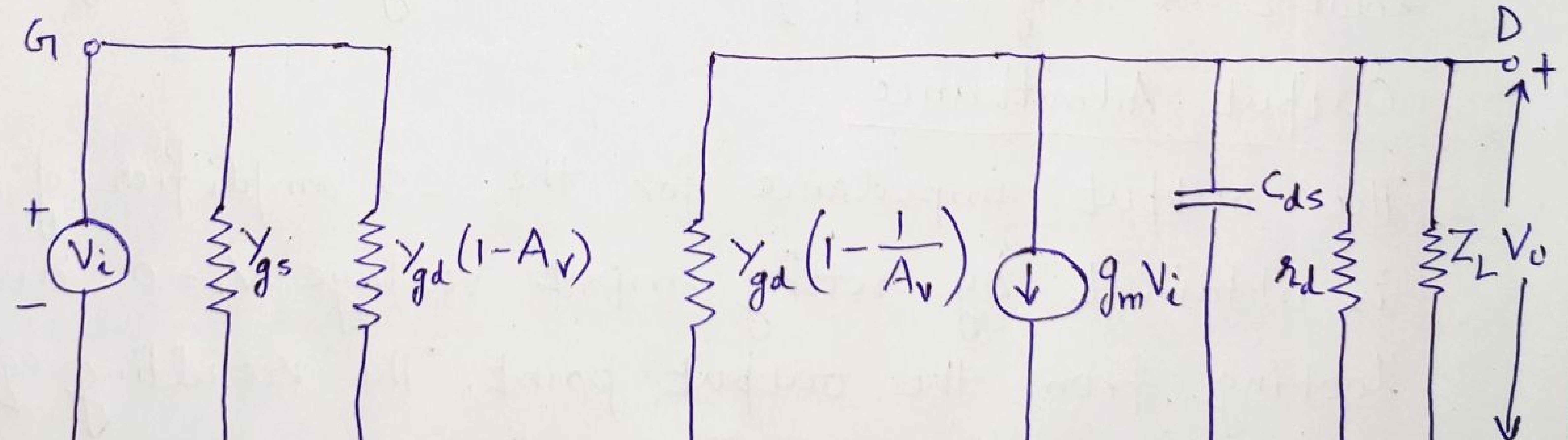


Figure 5. CS amplifier equivalent circuit after applying Miller's theorem

Hence, the input admittance is given by

$$Y_i = Y_{gs} + (1 - A_V) Y_{gd}$$

Input Capacitance (Miller Effect)

Now
$$A_V = -g_m Z_L'$$
where $Z_L' = Z_L \parallel r_d$.

For an FET with drain circuit resistance R_d, the voltage gain $A_V = -g_m R_d'$ where $R_d' = R_d \parallel r_d$.

$$\therefore \quad Y_i = Y_{gs} + (1 + g_m R_d') Y_{gd}$$
$$Y_i = j\omega C_{gs} + (1 + g_m R_d') j\omega C_{gd}$$
$$\frac{Y_i}{j\omega} = C_i = C_{gs} + (1 + g_m R_d') C_{gd}$$
Also note, $C_i = C_{gs} + (1 - A_V) C_{gd}$

The increase in input capacitance C_i over the capacitance from gate to source is the Miller effect.

As capacitive reactance decreases with increase in frequency, the resultant output impedance will be lower at higher frequencies, thereby reducing the gain.

Output Admittance

The output impedance for the CS amplifier of Figure 3 is obtained by setting input voltage $V_i = 0$ and looking from the output point. The resulting equivalent circuit is shown in Figure 6.

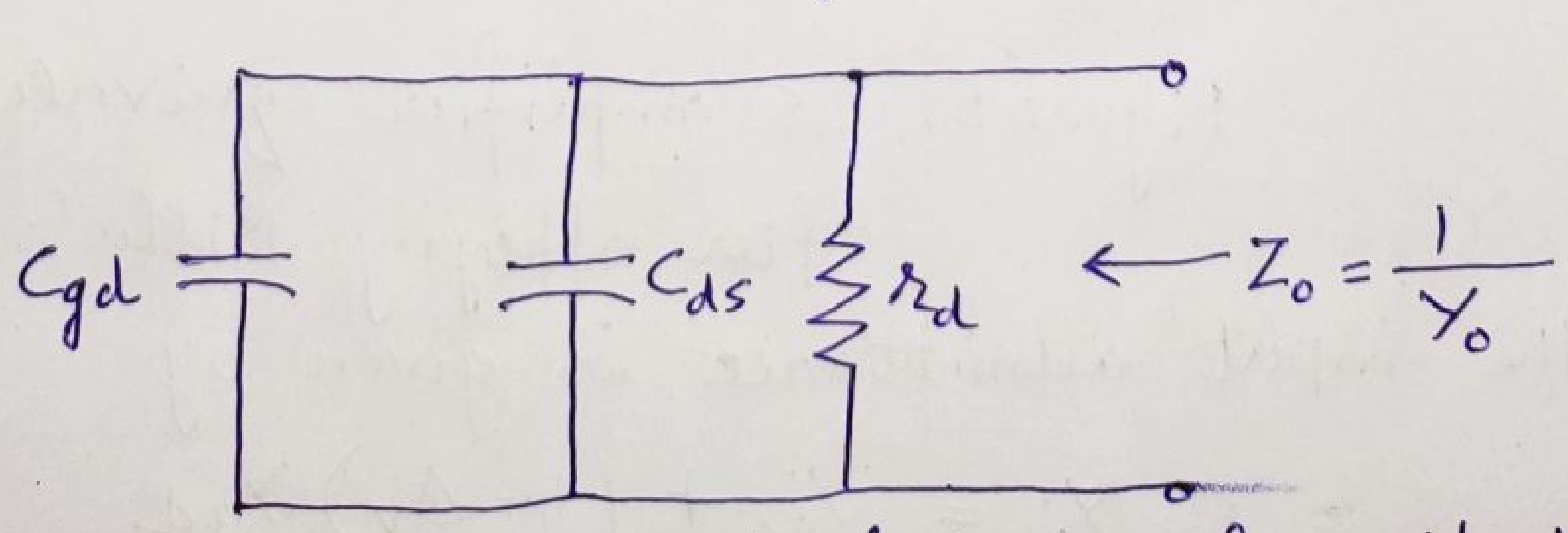


Figure 6. Calculation of output impedance

The output admittance with Z_L considered external to the CS amplifier circuit is given by

$$Y_o = g_d + Y_{ds} + Y_{gd}$$

High Frequency Response of a FET Amplifier

In the case of a FET amplifier, the high frequency characteristic of the amplifier is determined by the interelectrode and wiring capacitances. At high frequencies C_i (miller capacitance) will approach a short circuit equivalent and V_{gs} will drop and reduce the over all gain.

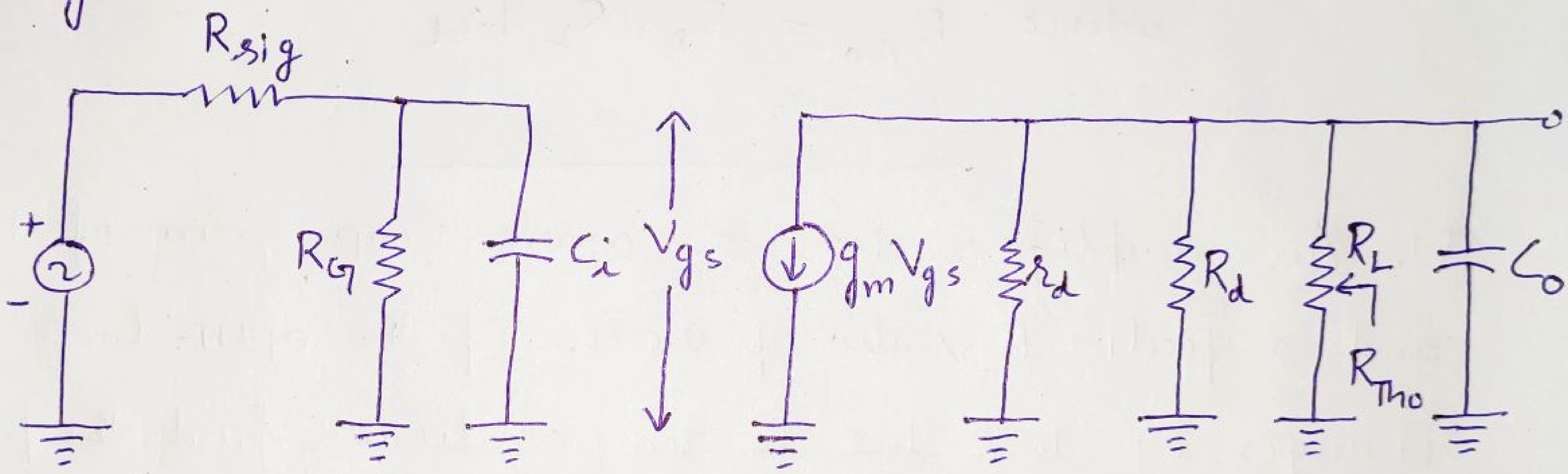


Figure 7. Modified high-frequency ac equivalent circuit (CS amplifier)

The cut off frequencies defined by the input and output circuits can be obtained by first finding the Thevenin equivalent circuits for each section as shown in Figure 8.

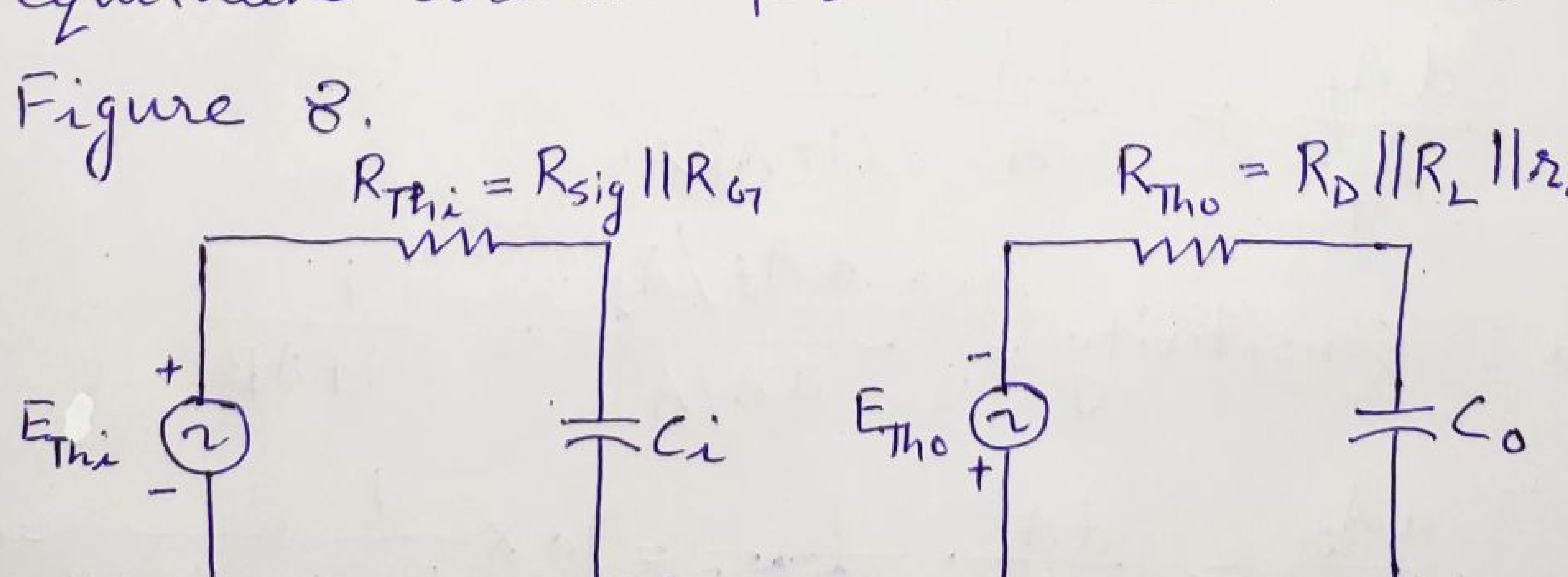


Figure 8. Thevenin equivalent circuit for (a) input (b) Output

For the input circuit,

$$f_{Hi} = \frac{1}{2\pi R_{Thi} C_i}$$

where $R_{Thi} = R_{sig} \| R_G$

and $C_i = C_{gs} + (1 - A_v) C_{gd}$

or $C_i = C_{gs} + (1 + g_m R_d') C_{gd}$

and for the output circuit,

$$f_{Ho} = \frac{1}{2\pi R_{Tho} C_o}$$

where $R_{Tho} = R_D \| R_L \| r_d$

Q1. An amplifier has an open-loop gain of 1000 and a feedback ratio of 0.04. If the open-loop gain changes by 10% due to temperature, find the percentage change in gain of the amplifier with feedback.

Solution: Given $A = 1000$, $\beta = 0.04$ and $\frac{dA}{A} = 10$

We know that the percentage change in gain of the amplifier with feedback is

$$\frac{dA_f}{A_f} = \frac{dA}{A} \cdot \frac{1}{(1 + A\beta)}$$

Note: $\text{Sensitivity} = \frac{dA_f / A_f}{dA / A} = \frac{1}{1 + A\beta}$

$$\therefore \frac{dA_f}{A_f} = \frac{dA}{A} \cdot \frac{1}{(1 + A\beta)} = 10 \times \frac{1}{1 + 1000 \times 0.04} = 0.25\%$$

Q. 2. An amplifier has a midband gain of 125 and a bandwidth of 250 KHz. (a). If 4% negative feedback is introduced, find the new bandwidth and gain. (b). If the bandwidth is to be restricted to 1 MHz, find the feedback ratio.

Solution: Given $A_{mid} = 125$, $BW = 250$ KHz

and $\beta = 4\% = 0.04$

(a) We know that

$$BW_f = (1 + A_{mid}\,\beta)\,BW$$

$$= (1 + 125 \times 0.04) \times 250 \times 10^3$$

$$BW_f = 1.5 \text{ MHz}$$

Gain with feedback, $A_f = \dfrac{A}{1 + A\beta} = \dfrac{125}{1 + 125 \times 0.04}$

$$A_f = \frac{125}{6} = 20.83$$

(b)

$$BW_f = (1 + A_{mid}\,\beta')\,BW$$

$$1 \times 10^6 = (1 + 125.\beta') \times 250 \times 10^3$$

$$\therefore \quad 1 + 125.\beta' = \frac{1 \times 10^6}{250 \times 10^3} = 4$$

$$\beta' = \frac{3}{125} = 0.024 = 2.4\%$$

Q. 3. A voltage-series negative feedback amplifier has a voltage gain without feedback of $A = 500$, input resistance $R_i = 3\,K\Omega$, output resistance $R_o = 20\,K\Omega$ and feedback ratio $\beta = 0.01$. Calculate the voltage gain A_f, input resistance R_{if} and output resistance R_{of} of the amplifier with feedback.

Solution: Given $A = 500$, $R_i = 3\ K\Omega$, $R_o = 20\ K\Omega$

and $\beta = 0.01$

Voltage gain $A_f = \dfrac{A}{1+A\beta} = \dfrac{500}{1+500\times 0.01}$

$$A_f = \frac{500}{6} = 83.33$$

Input resistance with feedback,

$$R_{if} = (1+A\beta)R_i$$

$$= (1+500\times 0.01)\times 3\times 10^{3}$$

$$R_{if} = 18\ K\Omega$$

Output resistance with feedback,

$$R_{of} = \frac{R_o}{1+A\beta}$$

$$R_{of} = \frac{20\times 10^{3}}{1+500\times 0.01} = 3.33\ K\Omega$$
