11

HOW TO MEASURE T

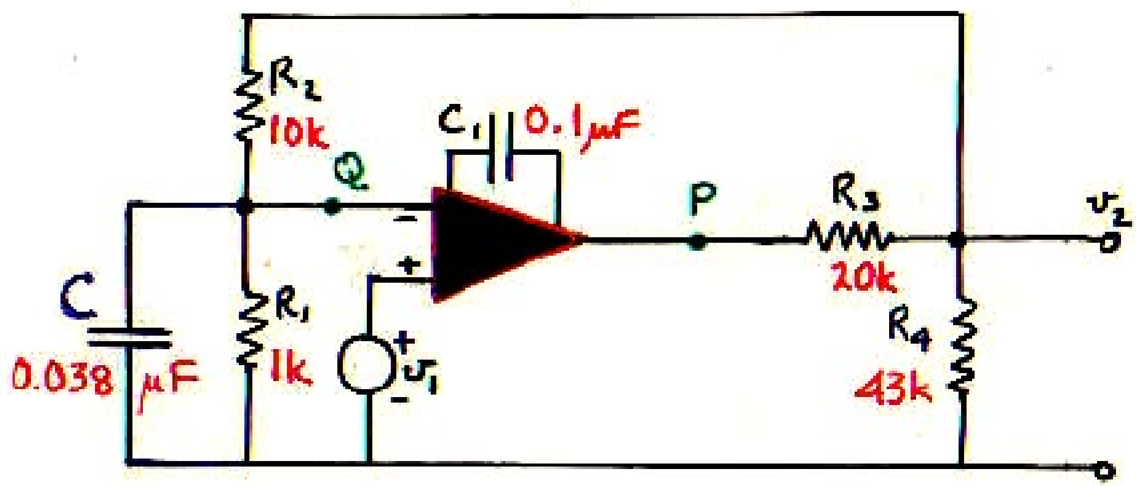
Measurement of Loop Gain

As for the calculation of loop gain, an injection point for the test signal must be found that satisfies two conditions:

1. Must be inside the feedback loop

2. Injected signal must add to the forward signal without affecting the impedance loading.

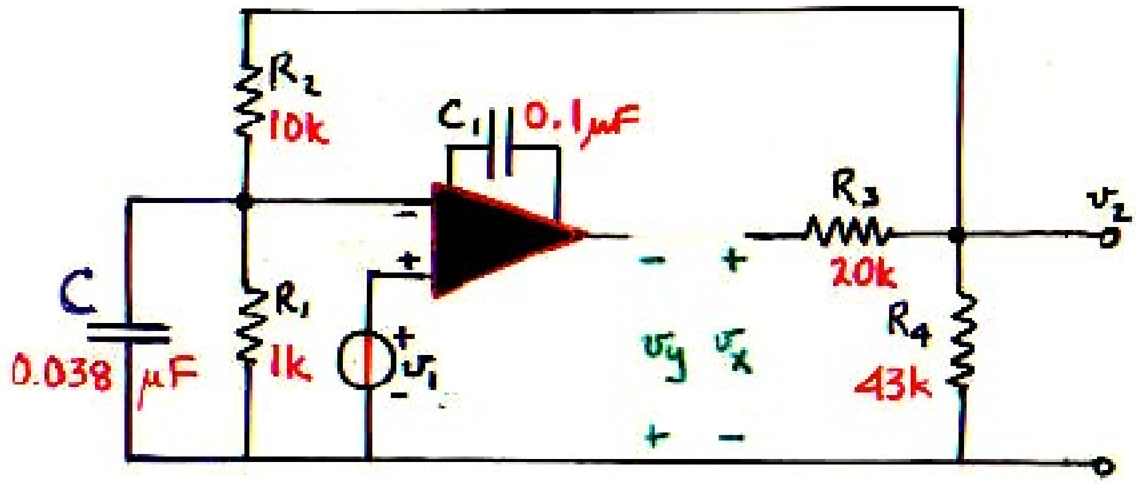
Example



Either point P or point Q could be used for series voltage injection; there is no suitable point for current injection.

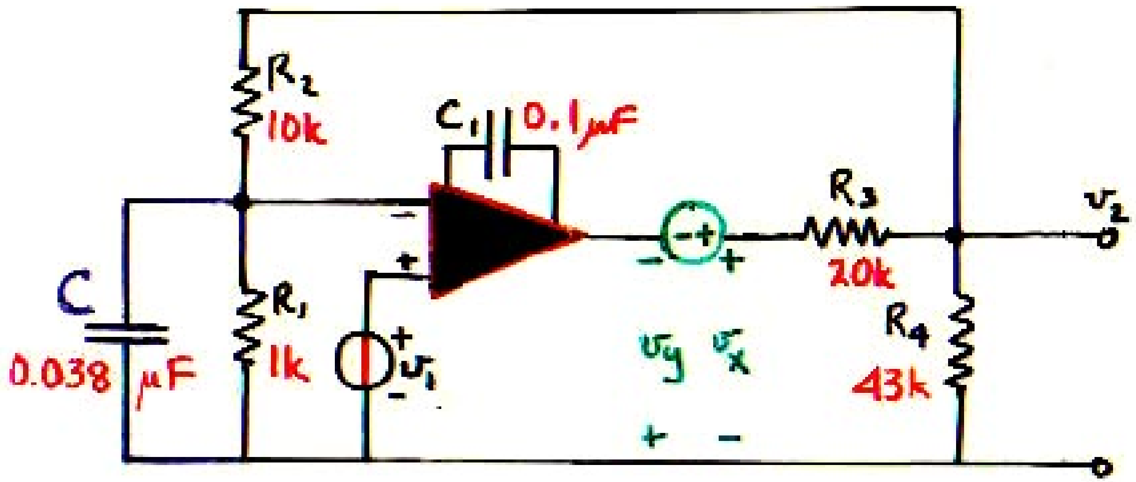
Experimentally, P is preferable because the signal levels are higher.

Example



The loop gain $T = \left.\frac{v_y}{v_x}\right|_{v_1=0}$ can then be measured in magnitude and phase by standard instrumentation.

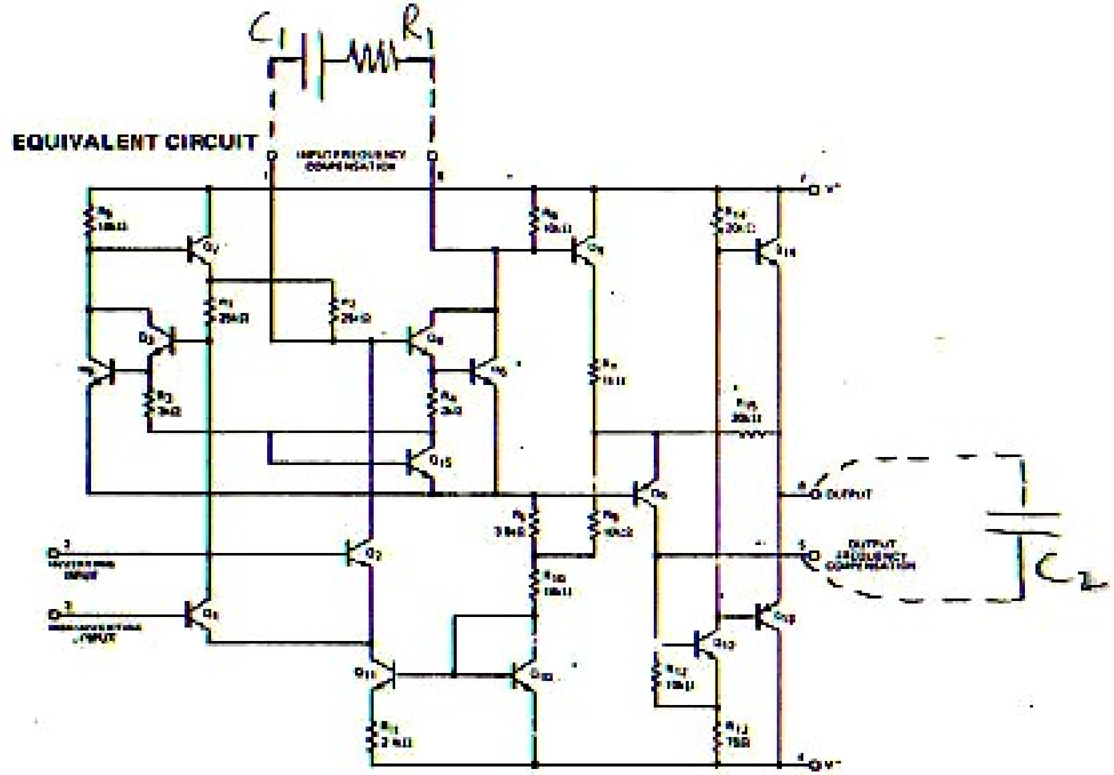
Example



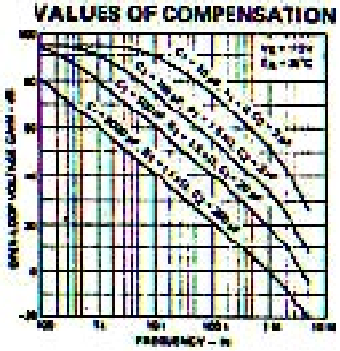
The loop gain $T = \left.\frac{v_y}{v_x}\right|_{v_i = 0}$ can then be measured in magnitude and phase by standard instrumentation.

In the normal design-analyze-measure sequence, the loop gain T is first predicted analytically.

EQUIVALENT CIRCUIT

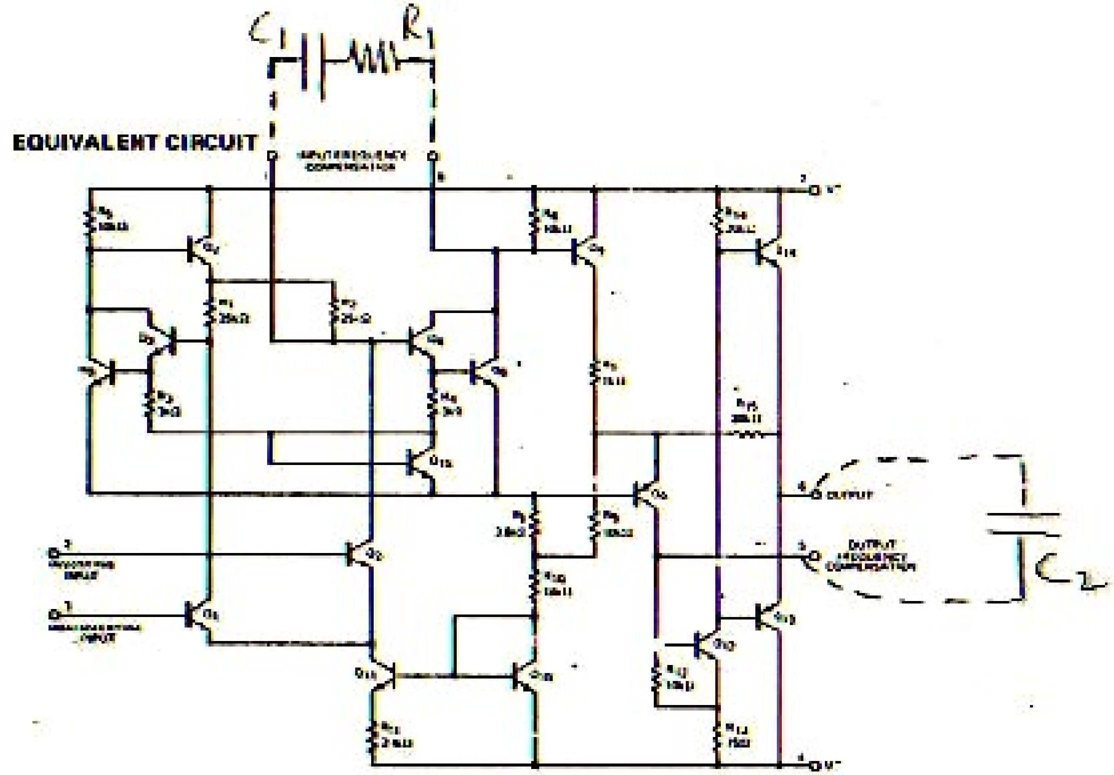


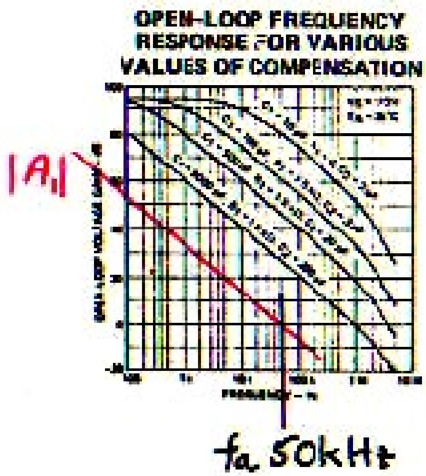
OPEN-LOOP FREQUENCY RESPONSE FOR VARIOUS VALUES OF COMPENSATION



With a 0.005uF compensating capacitor C_1, the gain-bandwidth product is 1 MHz

In the normal design-analyze-measure sequence, the loop gain T is first predicted analytically.

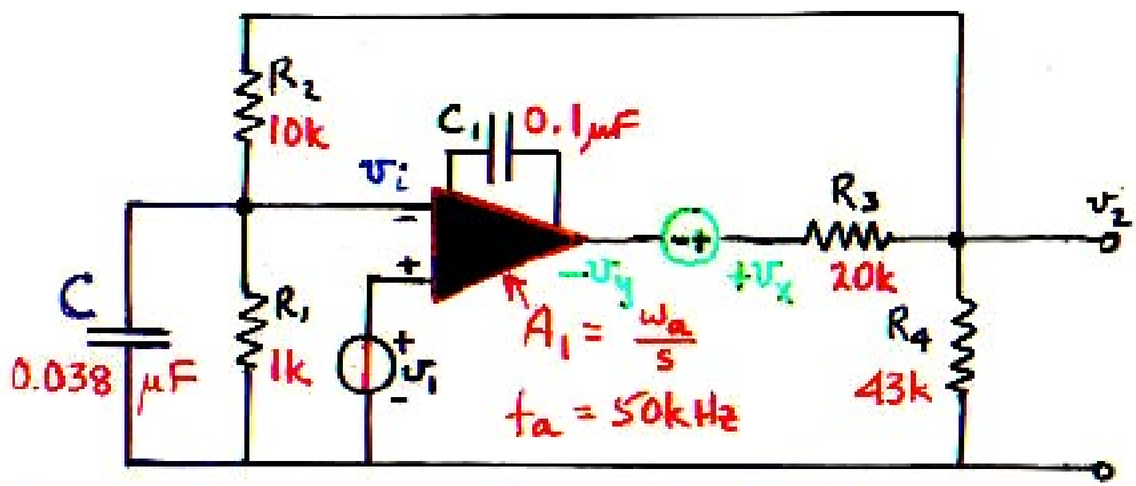




With a 0.005 uF compensating capacitor C_1, the gain-bandwidth product is 1 MHz. With $C_1 = 0.1\mu F$, the gbw product is $f_a = \frac{0.005}{0.1} \times 1 = 50\text{kHz}$.

So $A_1 = \frac{\omega_a}{s}$

Example



Without C: $T = \frac{v_y}{v_x} = \frac{v_y}{v_i}\frac{v_2}{v_x}\frac{v_i}{v_2}$

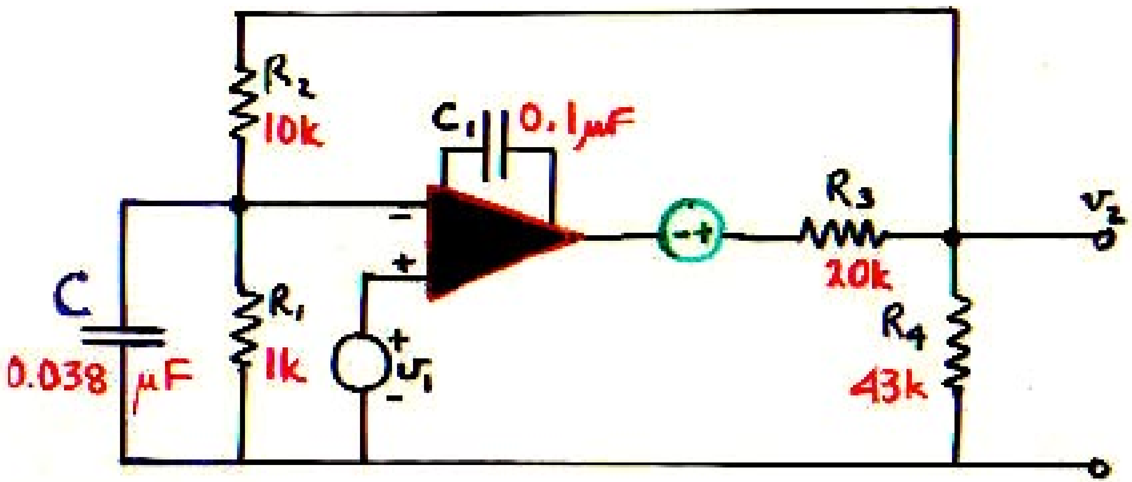
$= A_1 A_2 K$

$A_1 = \frac{\omega_a}{s}$ $\quad A_2 = \frac{R_4 \| (R_1 + R_2)}{R_3 + R_4 \| (R_1 + R_2)}$ $\quad K = \frac{R_1}{R_1 + R_2}$

$= 0.31$ $\quad = 0.091$

C introduces a pole at: $\omega_2 = \frac{1}{C[R_1 \| (R_2 + R_3 \| R_4)]}$ $\quad f_2 = 4.4$ kHz

Example



Hence

$$T = \frac{\omega_a}{s} A_2 K \frac{1}{1+\frac{s}{\omega_2}}$$

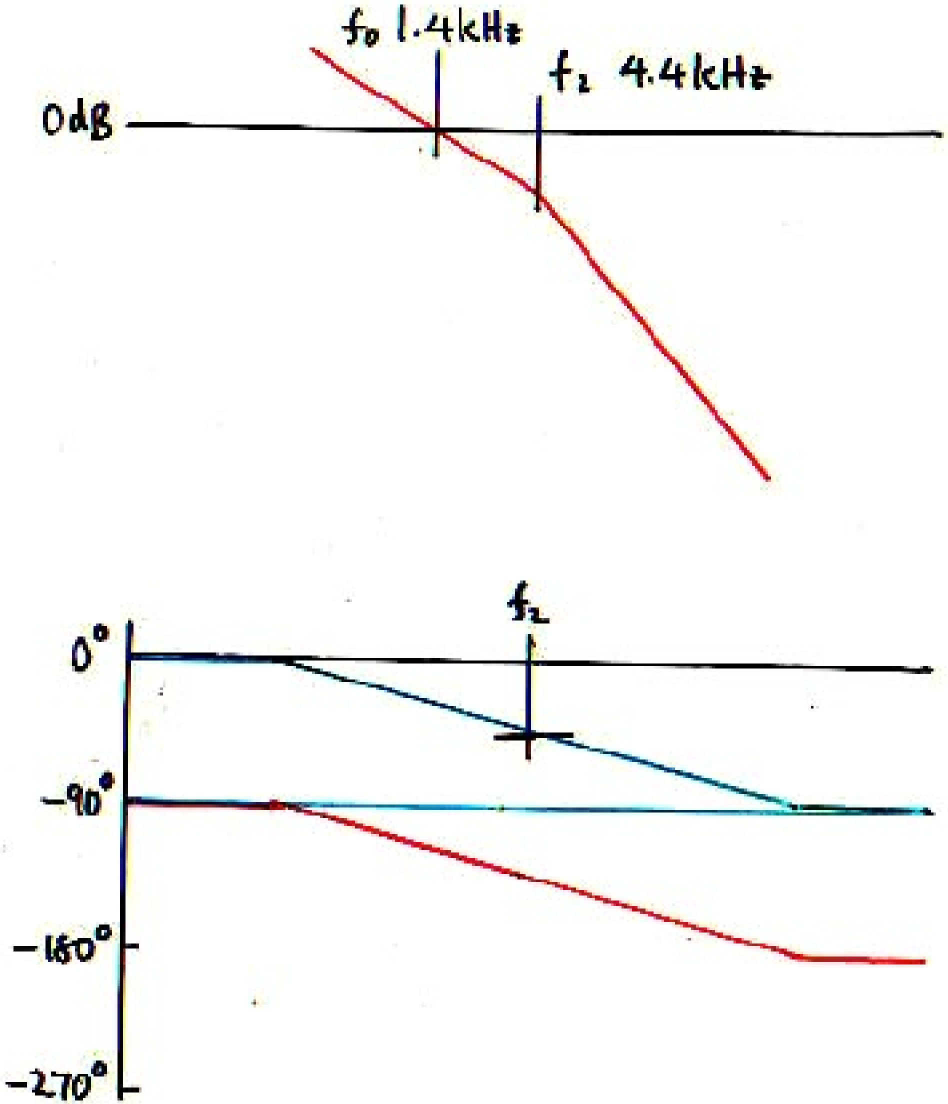
$$= \frac{1}{\frac{s}{\omega_0}\left(1+\frac{s}{\omega_2}\right)} \qquad \text{where } \omega_0 \equiv A_2 K \omega_a$$

$$f_0 = 1.4\,\text{kHz}$$

The Q of the closed-loop quadratic $D = T/(1+T)$ is

$$Q = \sqrt{\omega_0/\omega_2} = 0.56 \Rightarrow -5\text{dB}$$

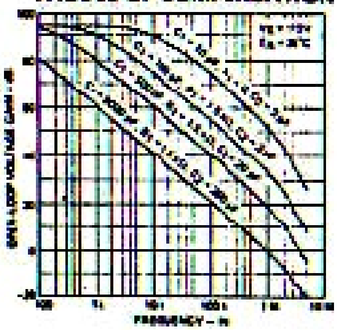
and the phase margin is $\phi_M = 73°$



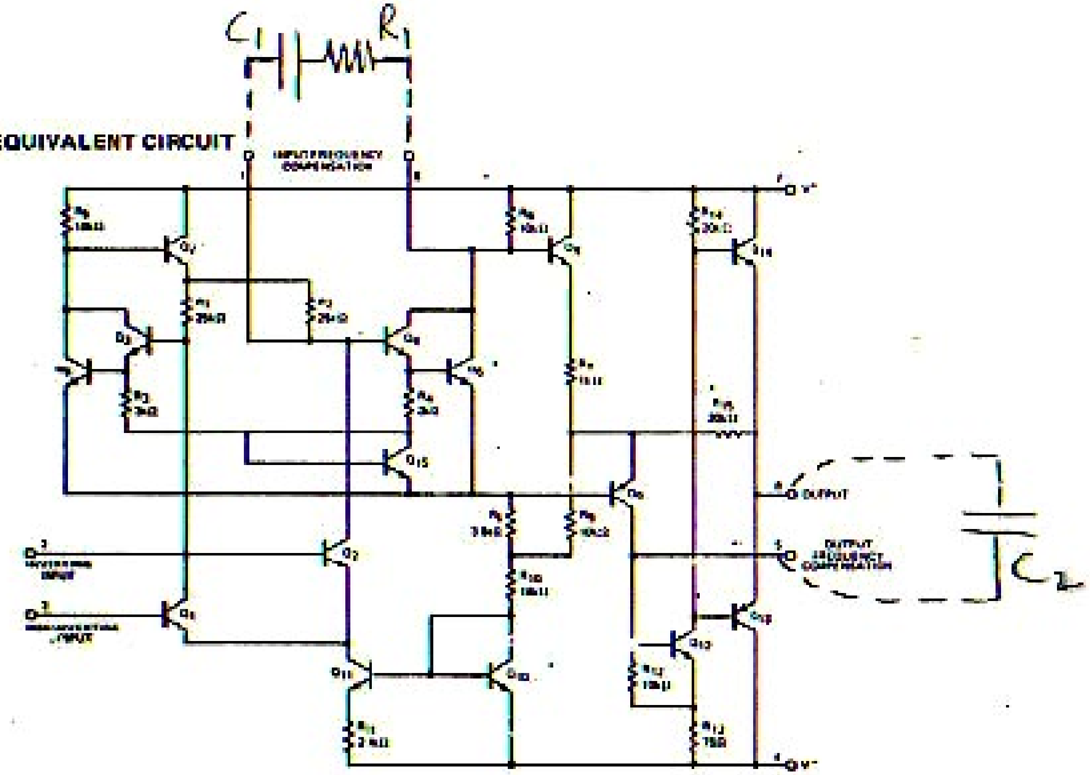
f0 1.4kHz
f2 4.4kHz
0dB
f2
0°
-90°
-180°
-270°

In the normal design–analyze–measure sequence, the loop gain T is first predicted analytically.

OPEN-LOOP FREQUENCY RESPONSE FOR VARIOUS VALUES OF COMPENSATION

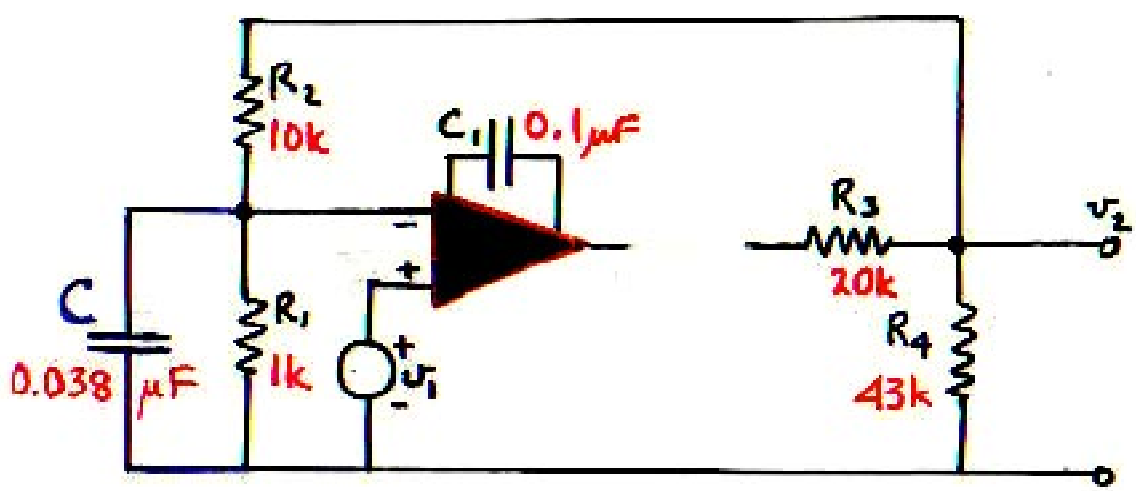


EQUIVALENT CIRCUIT

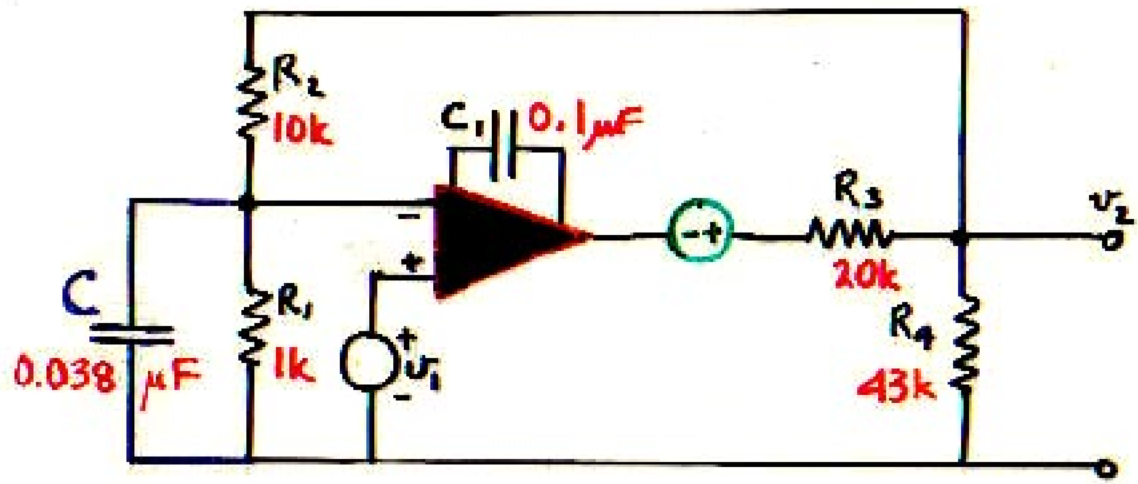


With a 0.005 uF compensating capacitor C_1, the gain-bandwidth product is 1 MHz

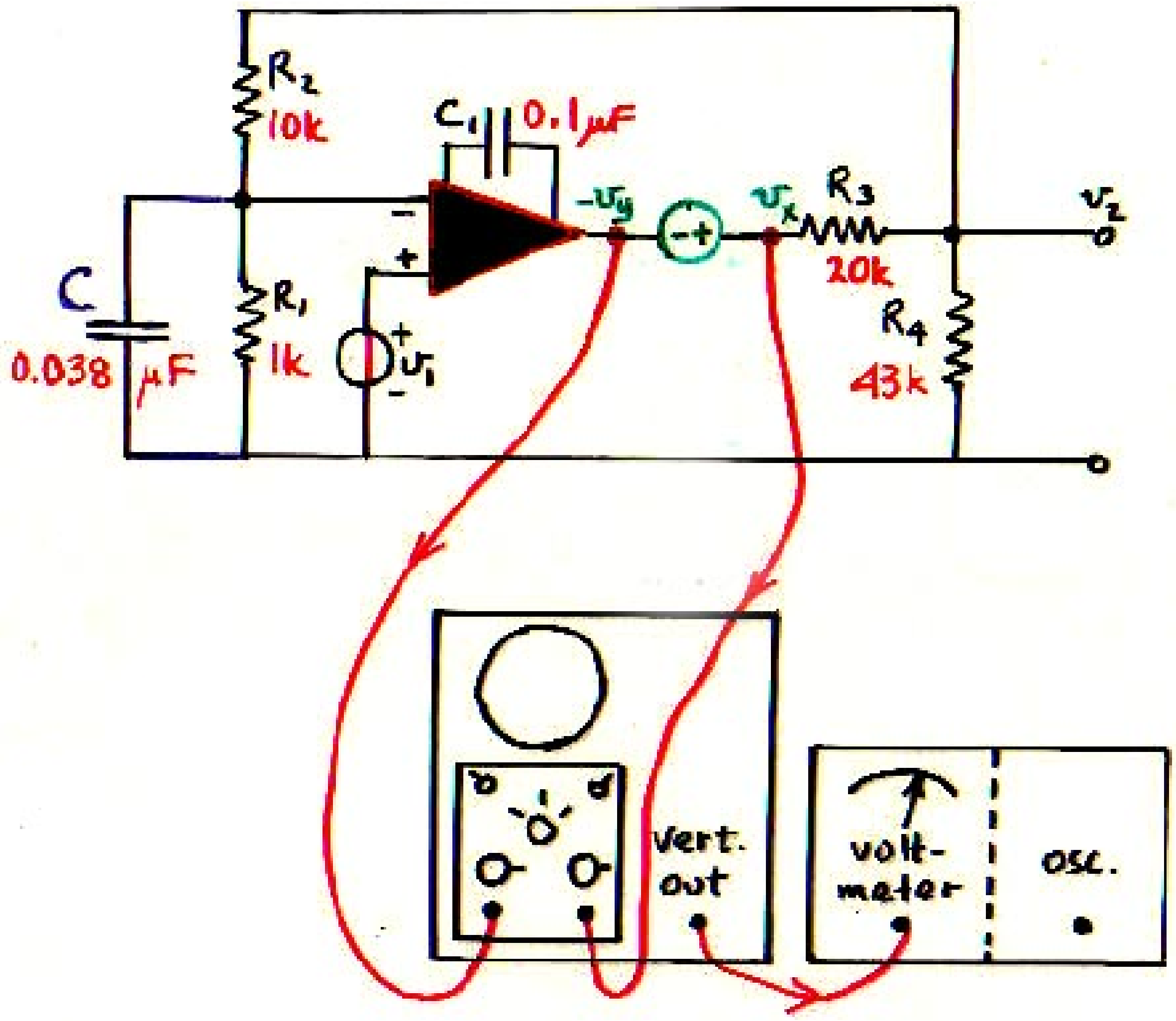
Example



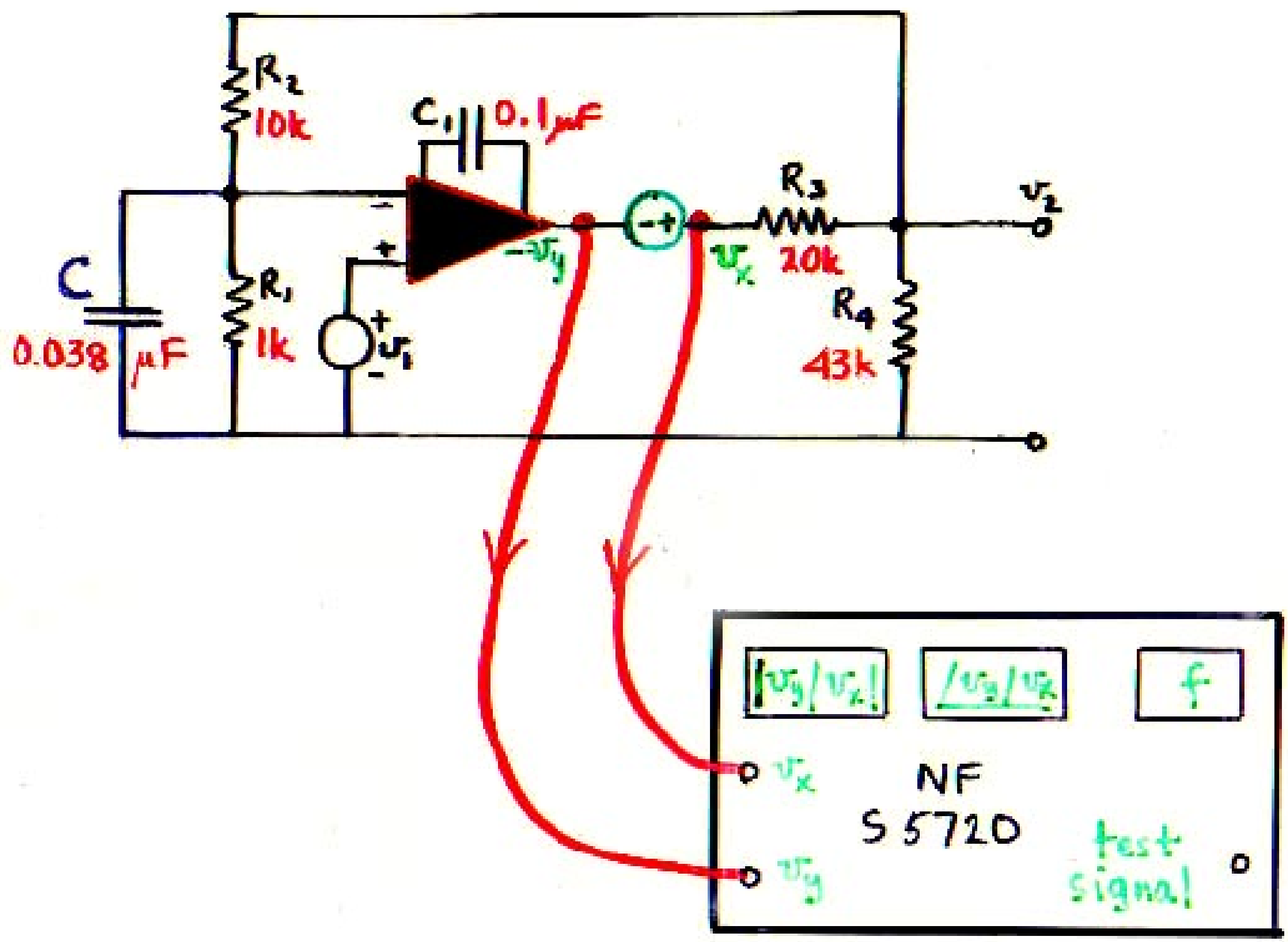
Example



Example   Measurement instrumentation:

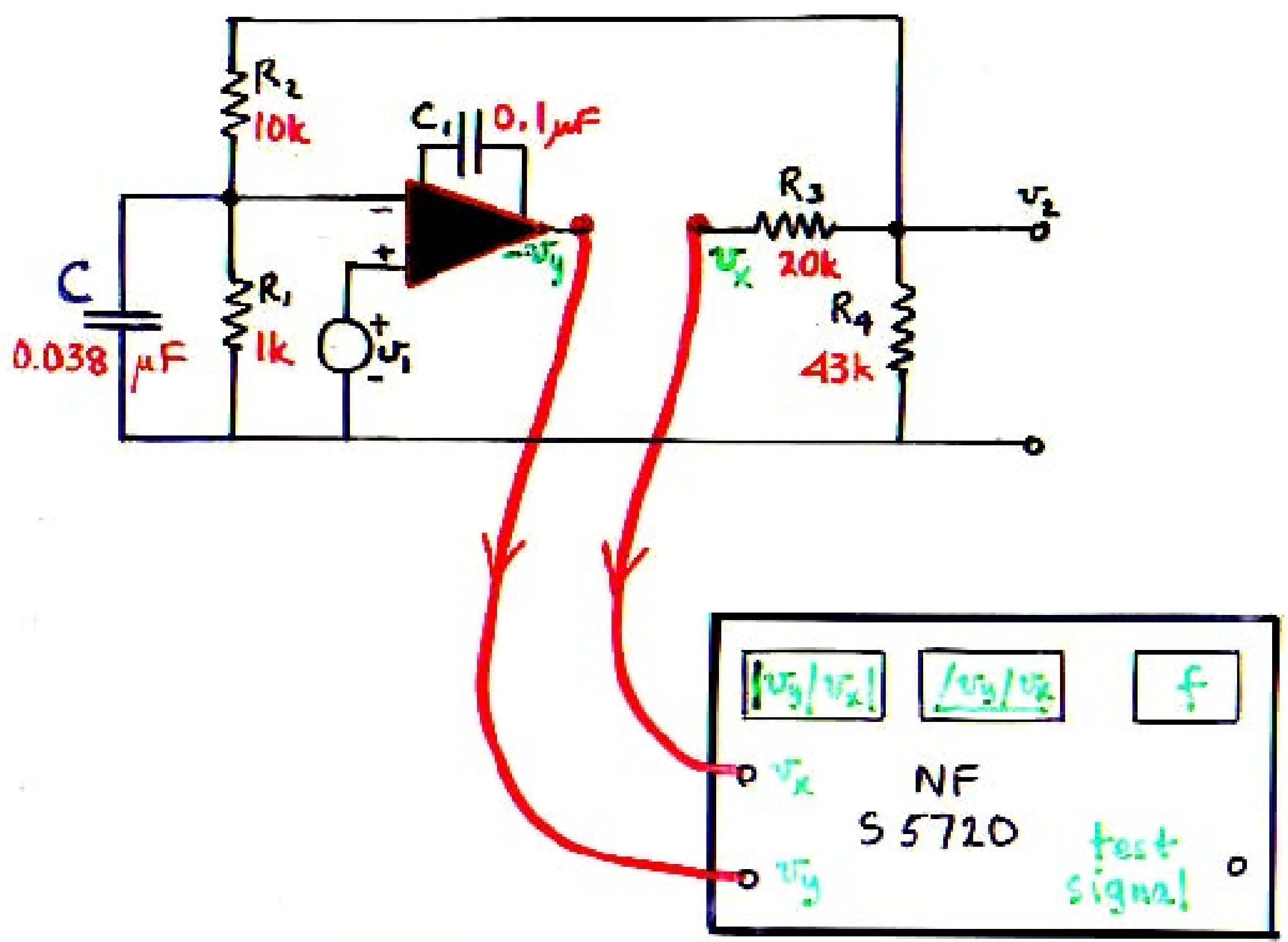


Example



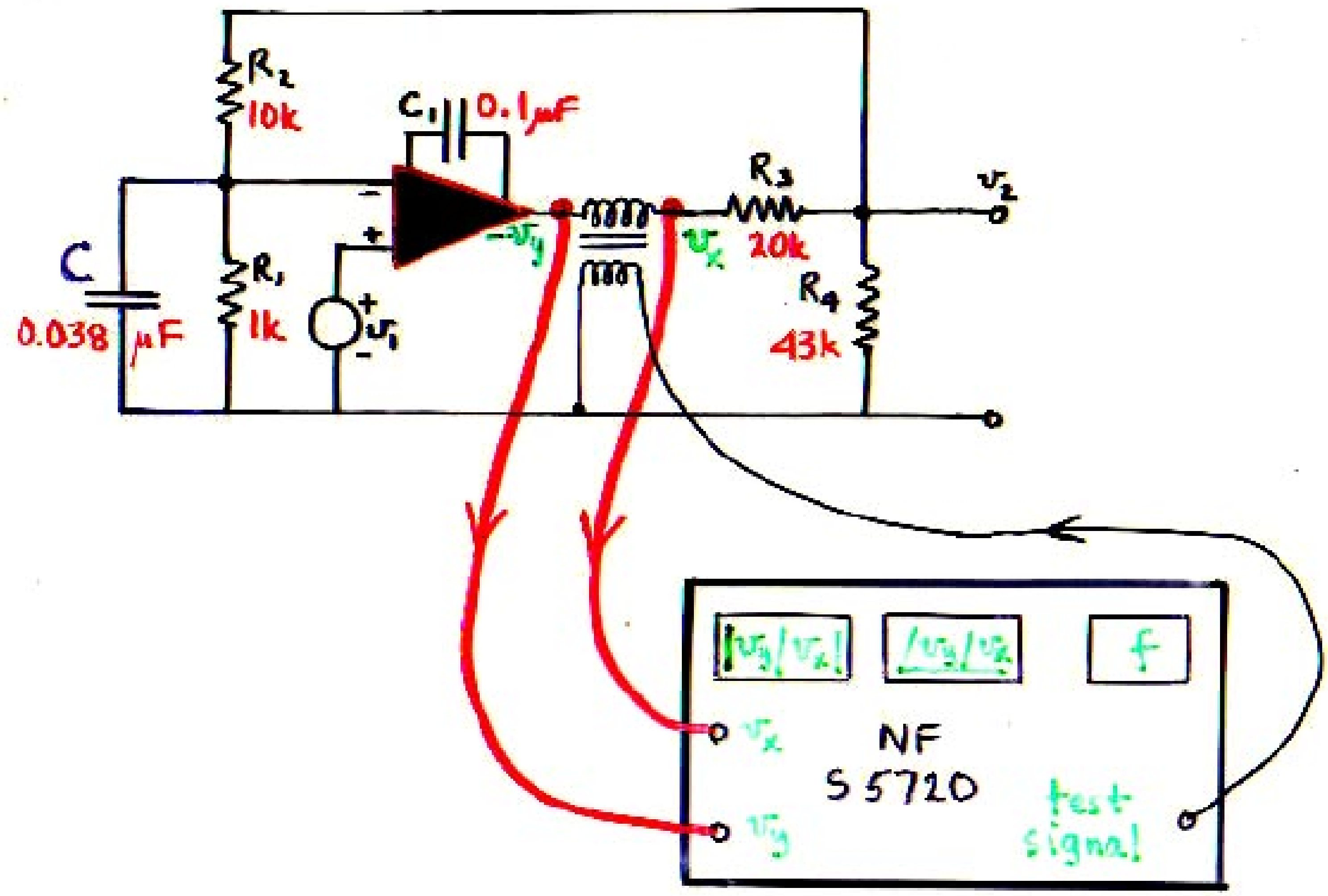
R_2
10k
C_1
0.1μF
$-v_y$
v_x
R_3
20k
v_2
C
0.038 μF
R_1
1k
v_1
R_4
43k
$|v_y/v_x|$
$\angle v_y/v_x$
f
v_x
v_y
NF
S 5720
test
signal

Example



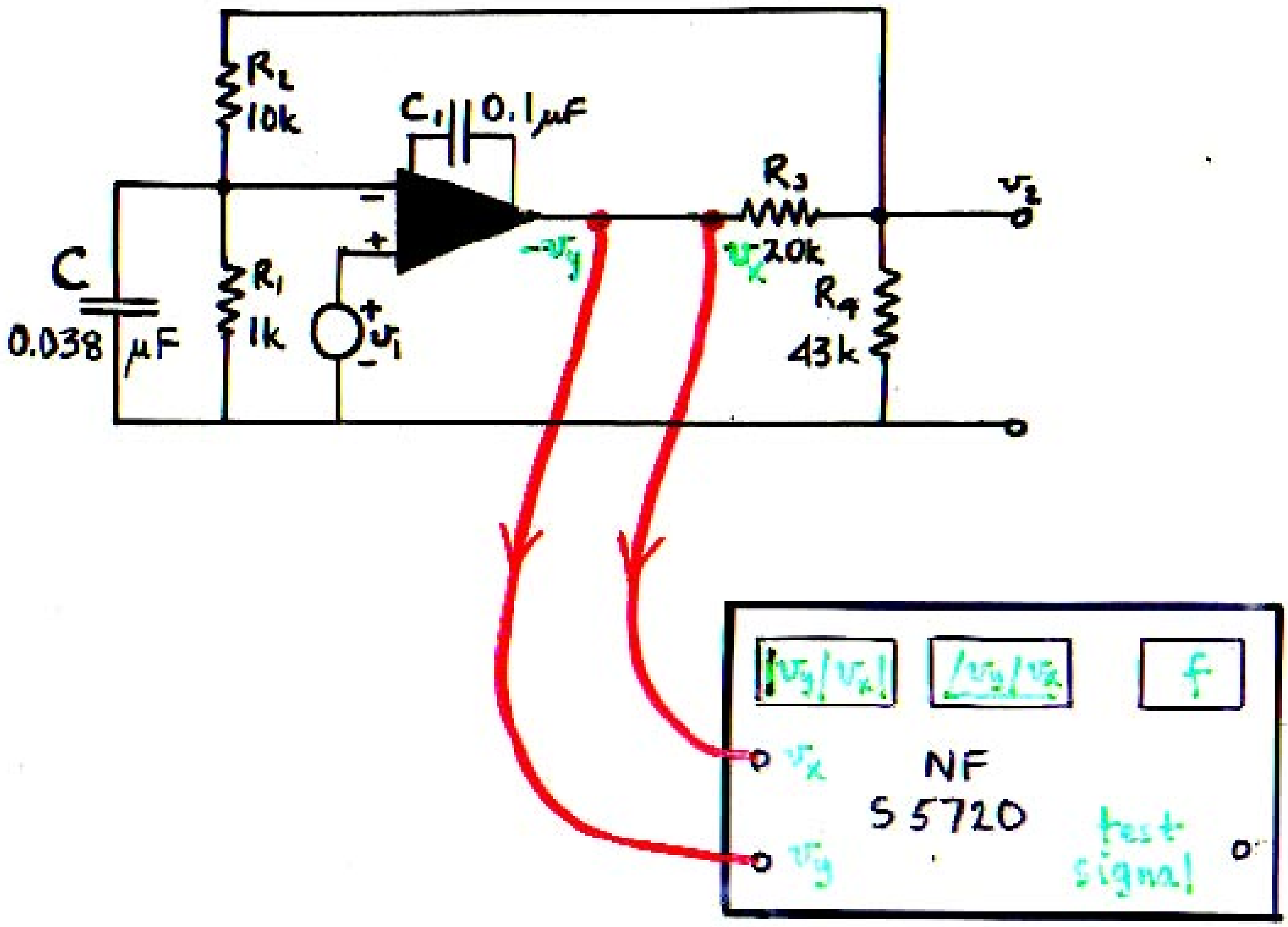
R2
10k
C1
0.1μF
C
0.038 μF
R1
1k
v1
-vy
vx
R3
20k
v2
R4
43k
|vy/vx|
∠vy/vx
f
vx
vy
NF
S 5720
test
signal

Example



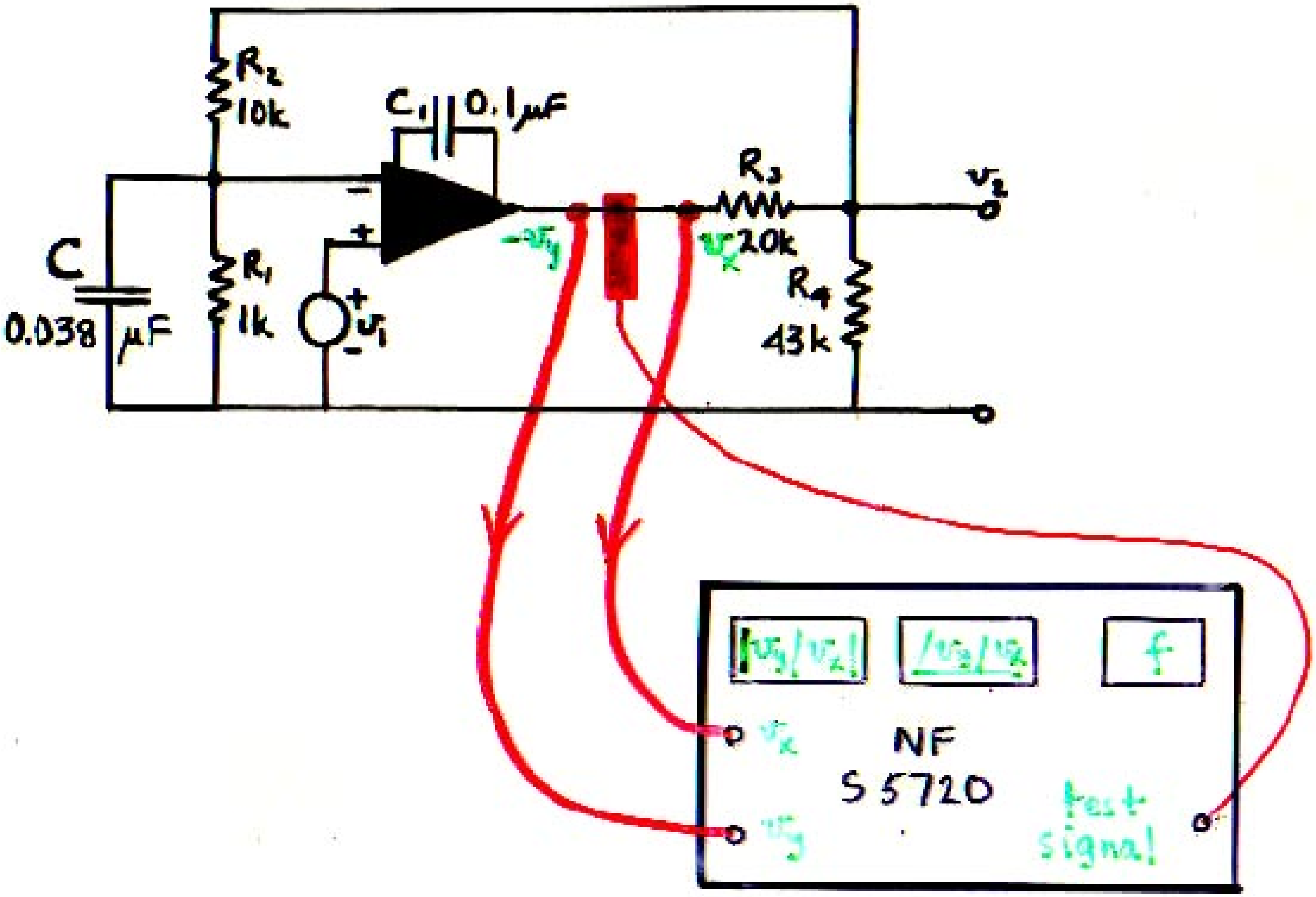
An isolation transformer is needed to couple in the injected signal.

Example



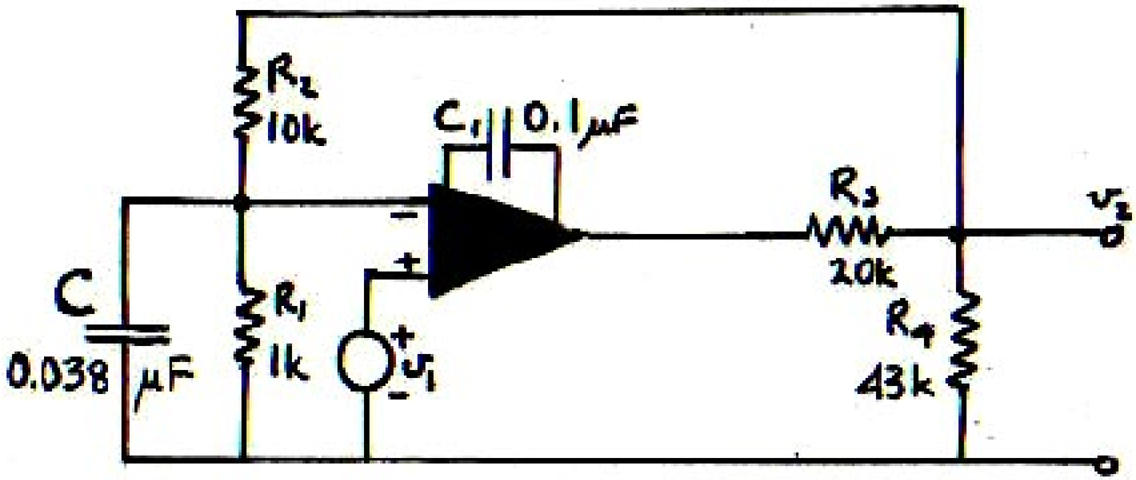
R_2
10k
C_1
0.1 μF
R_3
v_2
$-v_y$
v_x
20k
C
R_1
R_4
0.038 μF
1k
v_1
43k
$|v_y/v_x|$
$\angle v_y/v_x$
f
v_x
v_y
NF
S 5720
test signal

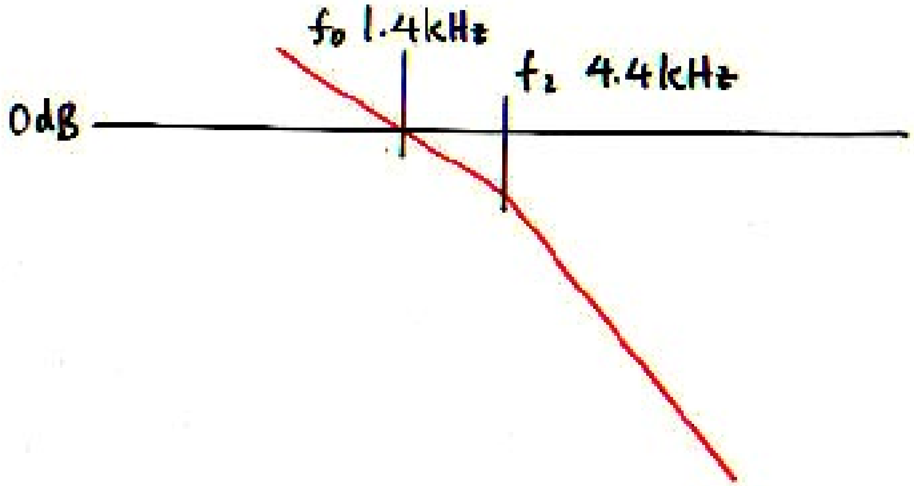
Example



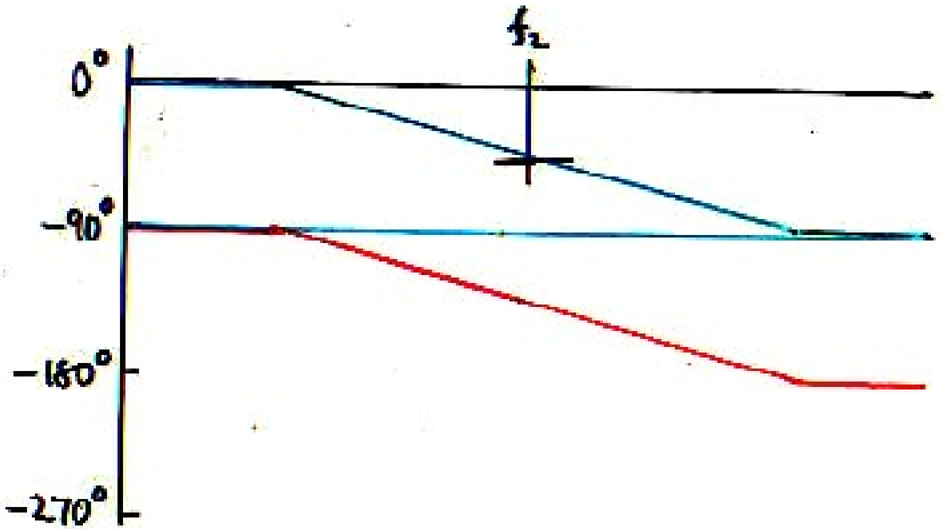
R2
10k
C1
0.1μF
R3
20k
v2
C
0.038 μF
R1
1k
v1
-vy
vx
R4
43k
|vy/vx|
/vy/vx
f
vx
vy
NF
S 5720
test
signal

Example

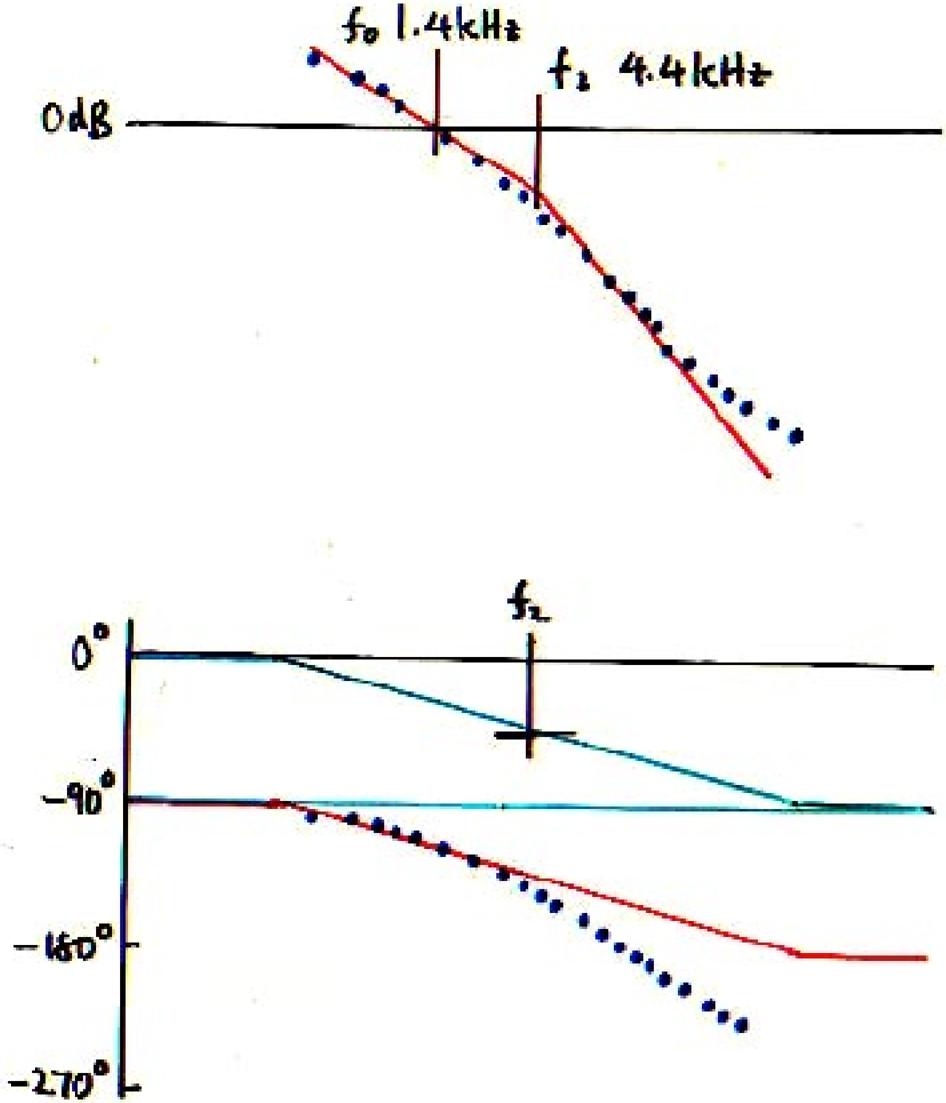




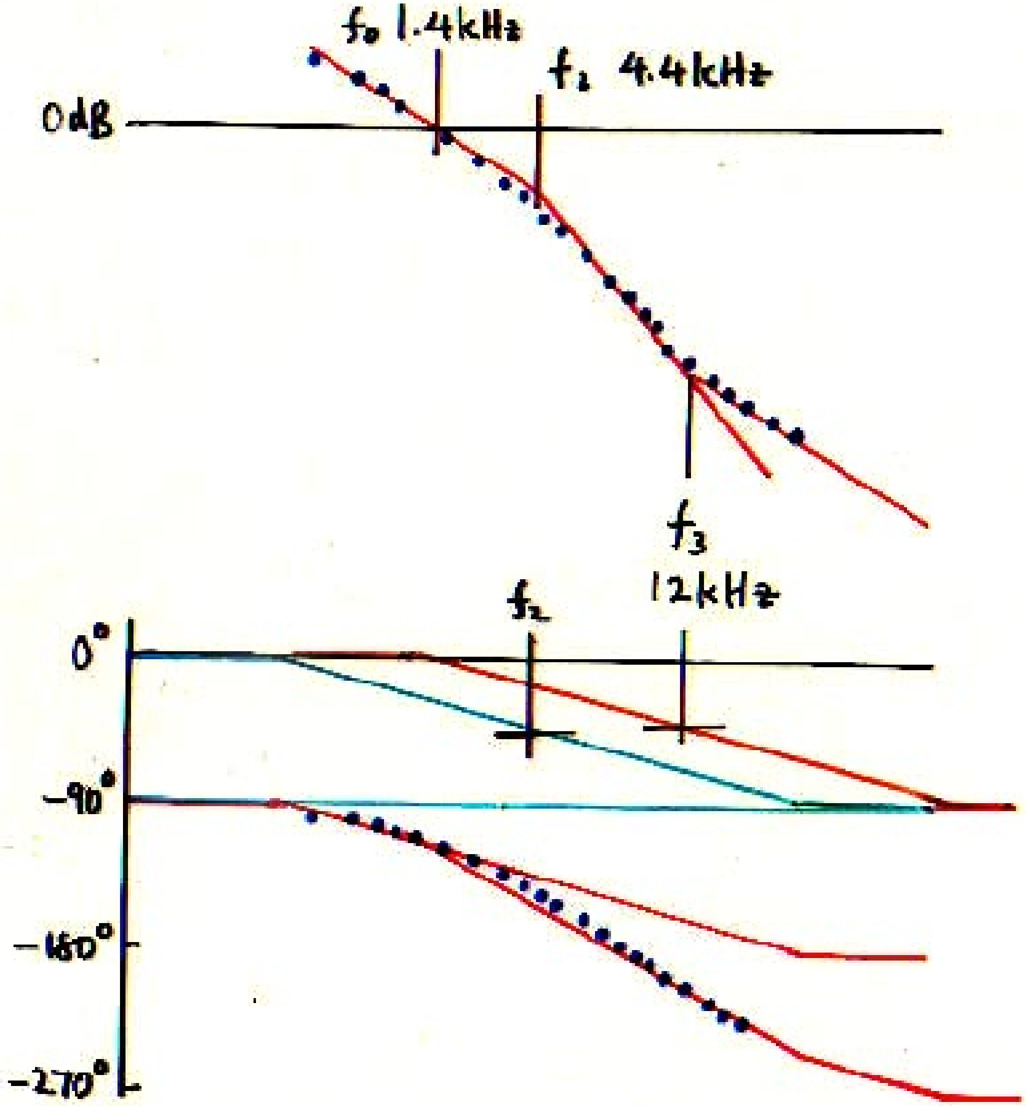
f0 1.4kHz
f2 4.4kHz
0dB



f2
0°
-90°
-180°
-270°



f_0 1.4kHz
f_2 4.4kHz
0dB
f_2
0°
-90°
-180°
-270°



f0 1.4kHz
f1 4.4kHz
0dB
f3
12kHz
f2
0°
-90°
-180°
-270°

Measurements indicate a right half-plane zero at $f_3 = 12\,kHz$.

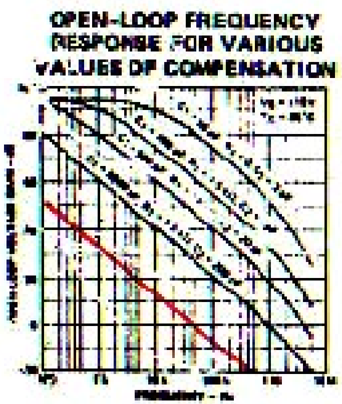
Hence the actual loop gain is

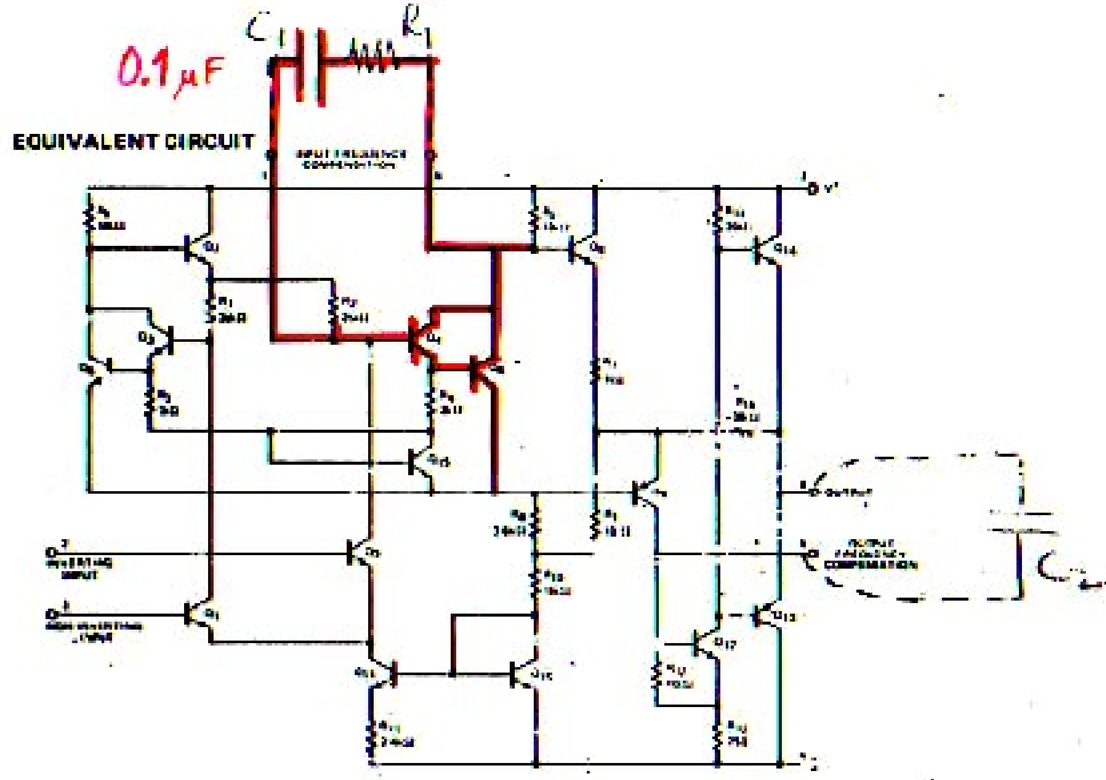
$$T = \frac{1 - \frac{s}{\omega_3}}{\frac{s}{\omega_0}\left(1 + \frac{s}{\omega_2}\right)}$$

and the actual phase margin is

$$\phi_M = 73° - \tan^{-1}\frac{\omega_0}{\omega_3} = 73° - 7° = 66°$$

In the normal design-analyze-measure sequence, the loop gain T is first predicted analytically.





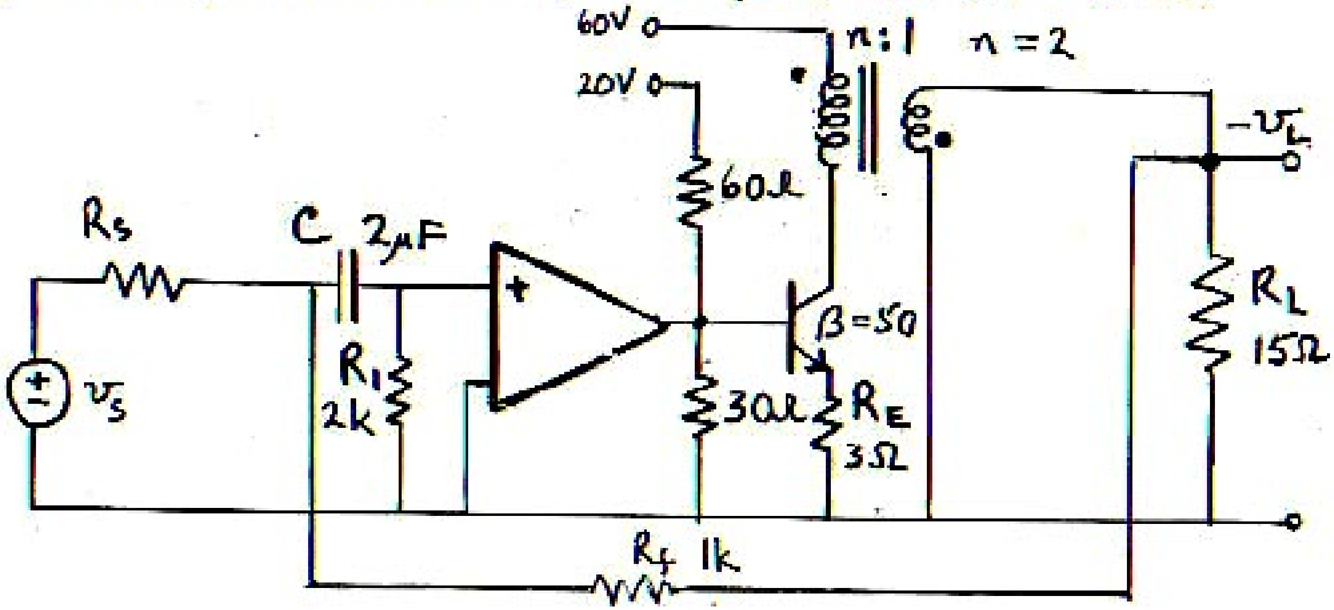
With a $0.005\mu F$ compensating capacitor C_1, the gain-bandwidth product is 1 MHz

Generalization: Implementation of Series Voltage Injection of Loop Gain Test Signal

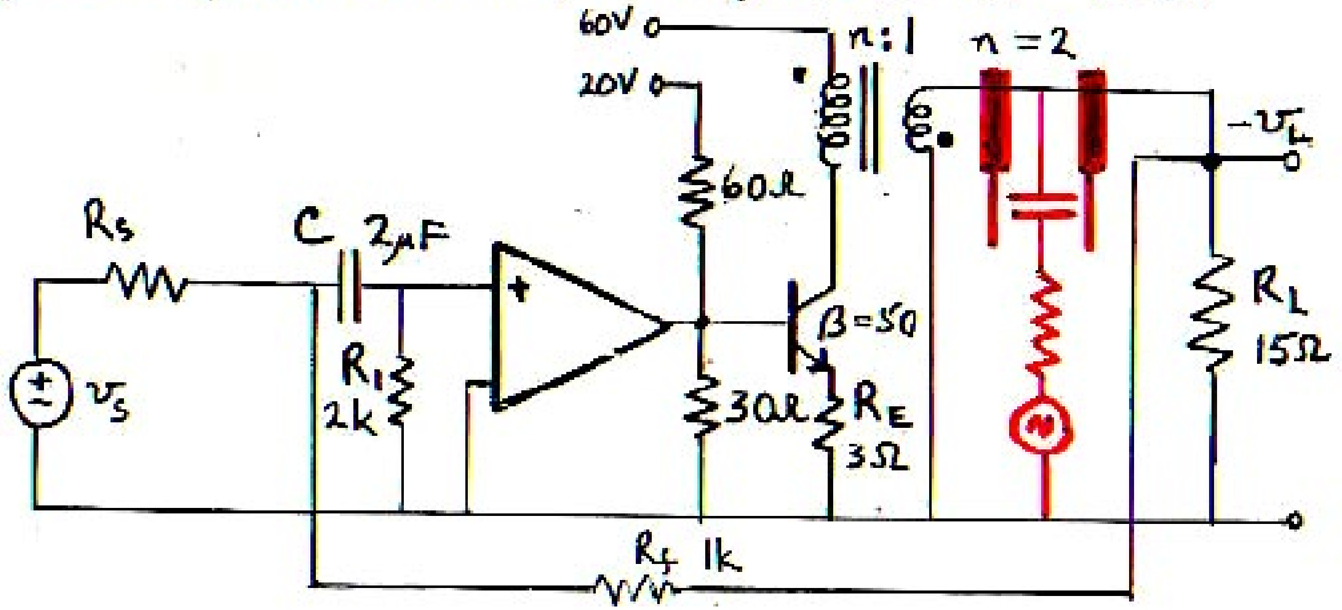
The necessary floating injection signal can be obtained from a grounded source by "backwards" use of an ac current probe as a "one-turn secondary isolation transformer."

Higher signal injection can be obtained by wrapping more than one secondary turn around the probe.

Single-ended Class A audio feedback power amplifier, based on the same power stage previously discussed. The driver opamp has a gain $A_1 = A_{10}/((1+s/\omega_A)$, where $A_{10} = 8dB$ and $f_A = 2kHz$, and an output impedance of 4.5Ω



Single-ended Class A audio feedback power amplifier, based on the same power stage previously discussed. The driver opamp has a gain $A_1 = A_{10}/(1+s/\omega_A)$, where $A_{10} = 8\,dB$ and $f_A = 2\,kHz$, and an output impedance of $4.5\,\Omega$.



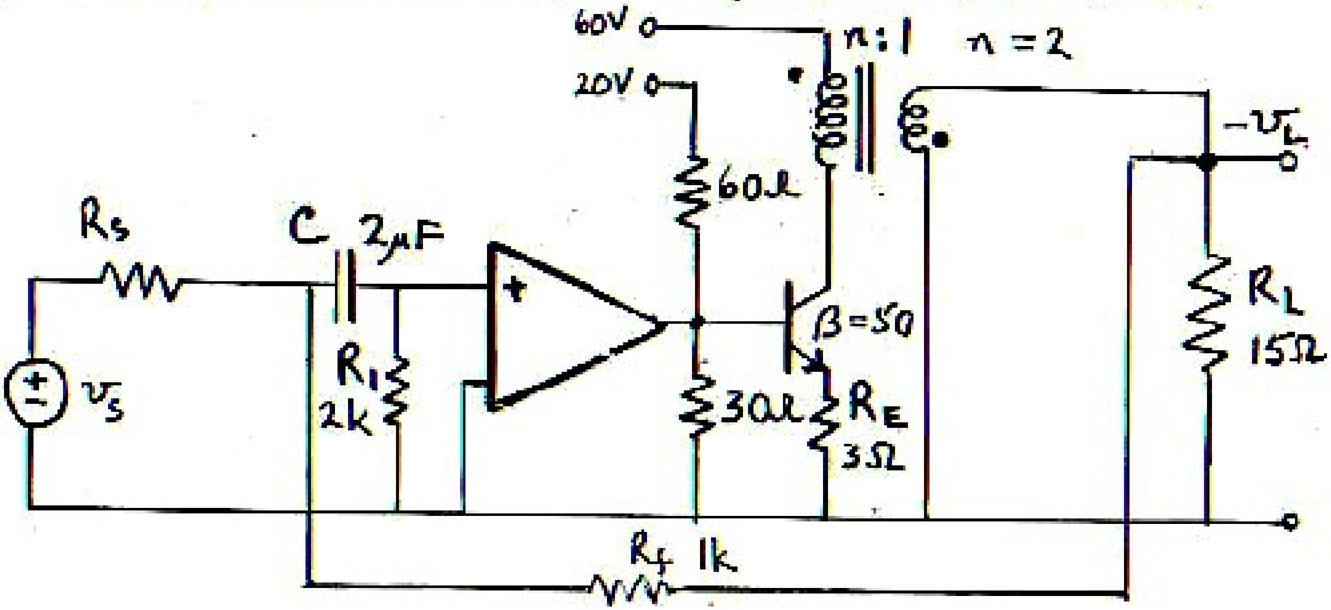
Injection at a non-ideal point:

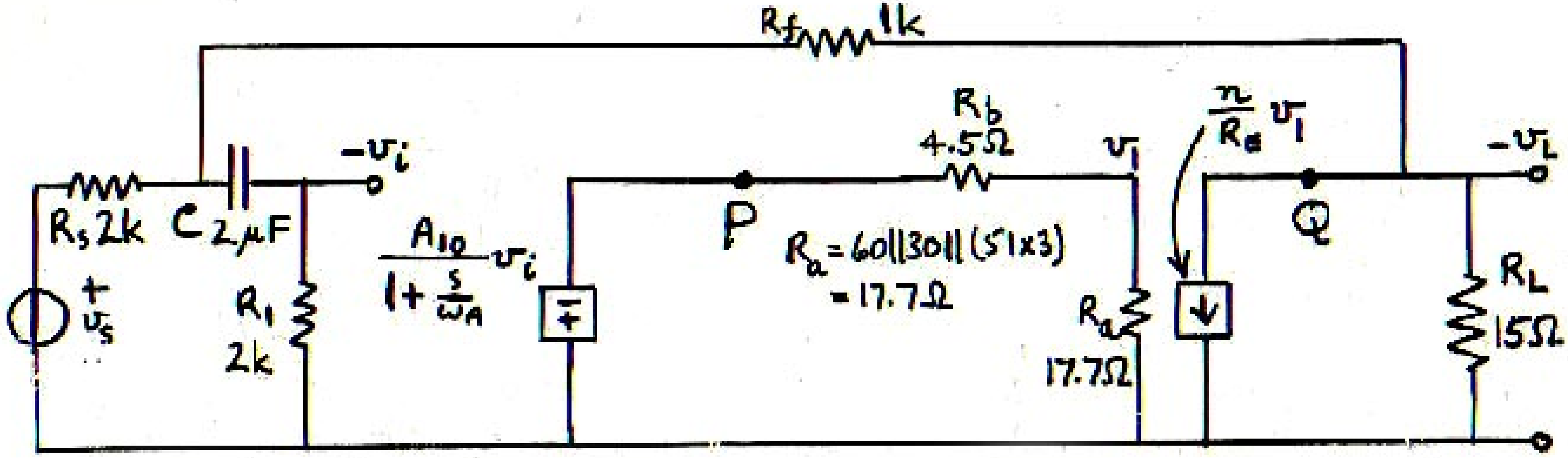
There are two conditions upon the choice of injection point:

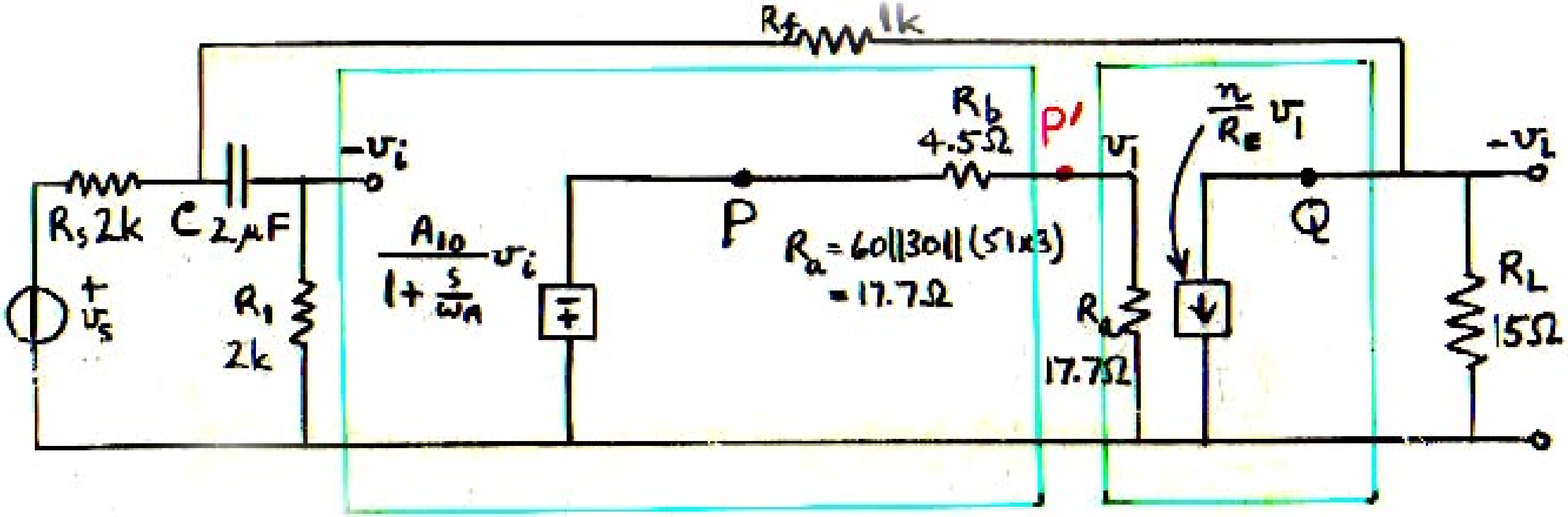
1. Must be inside the feedback loop
2. Injected signal must add to the forward signal without affecting the impedance loading.

What happens if #2 is not satisfied?

Single-ended Class A audio feedback power amplifier, based on the same power stage previously discussed. The driver opamp has a gain $A_1 = A_{10}/((1+s/\omega_A)$, where $A_{10} = 8dB$ and $f_A = 2kHz$, and an output impedance of 4.5Ω



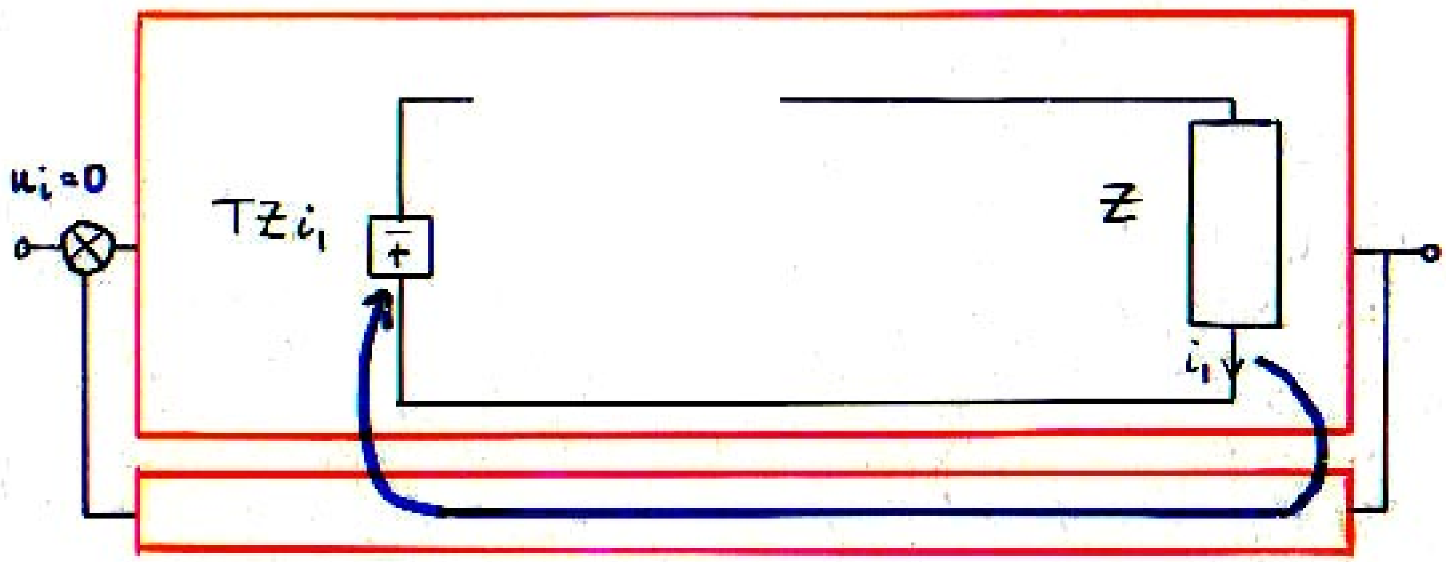

Rf 1k
Rb
4.5Ω
$-v_i$
v_1
$\frac{n}{R_B} v_1$
$-v_L$
R_s 2k
C 2μF
P
Q
$\frac{A_{10}}{1+\frac{s}{\omega_A}} v_i$
$R_a = 60\|30\|(51\times3)$
= 17.7Ω
+
v_s
R_1
2k
R_a
17.7Ω
R_L
15Ω



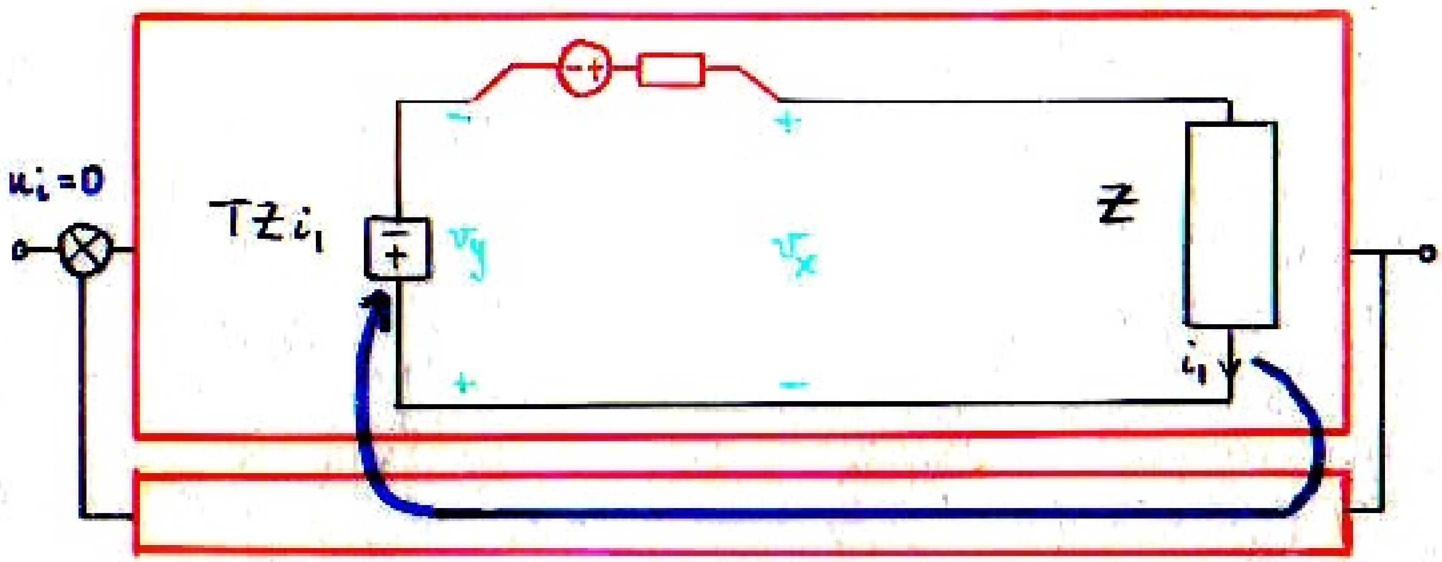
The voltage injection point P is not accessible.

The nearest accessible point is P.′

Consider, in general, voltage injection at a nonideal point. Also, take into account nonzero impedance of the injecting source.

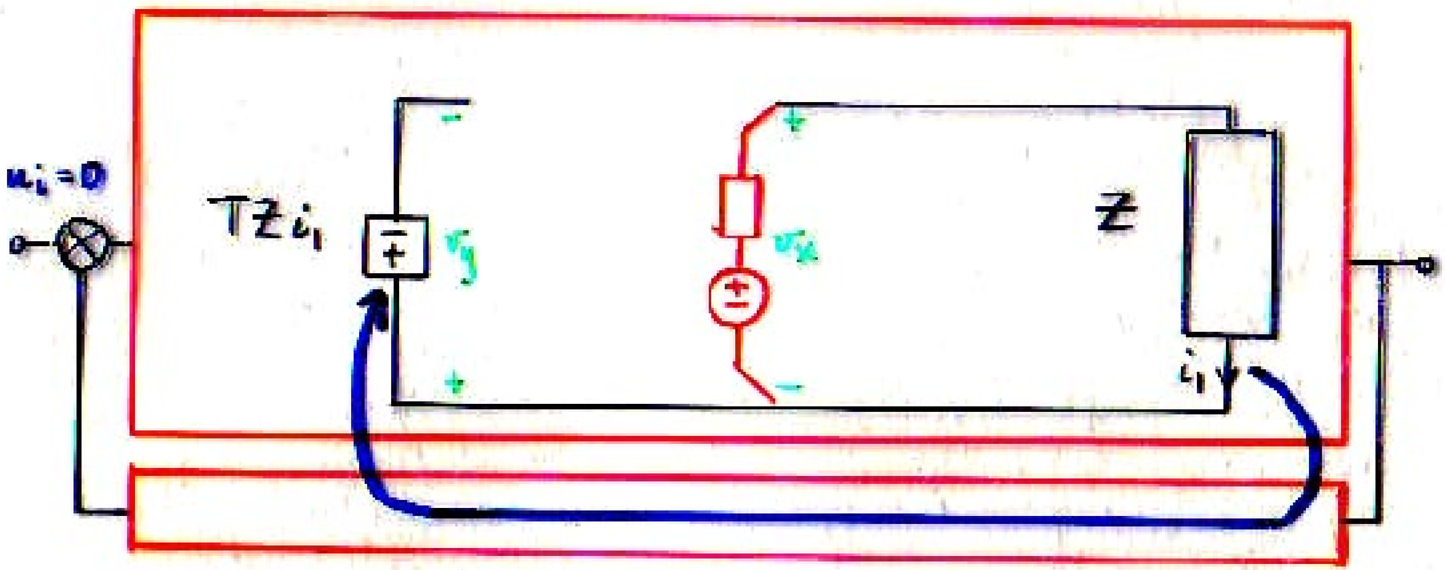


$u_i = 0$
TZi_1
Z
i_1



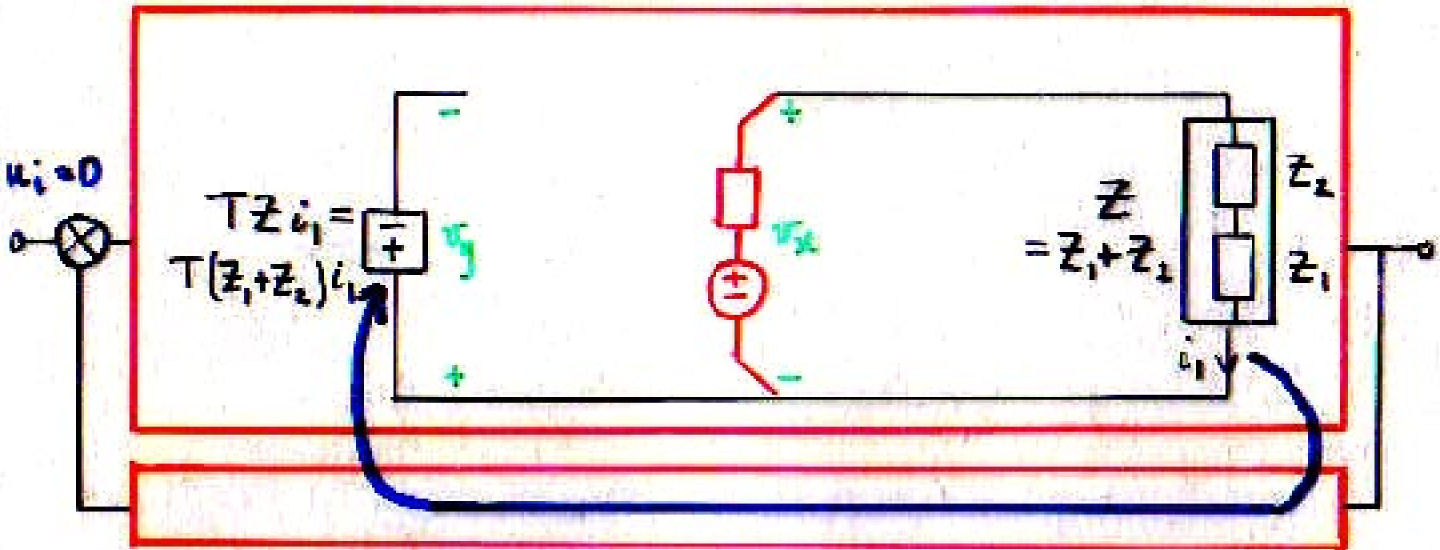
Loop gain by injection of a test signal at an "ideal" point:

$$T_v \equiv \frac{v_y}{v_x} = T \quad \leftarrow \quad \begin{cases} v_y = TZi_1 \\ i_1 = \dfrac{v_x}{Z} \end{cases}$$



Loop gain by application of a test signal to the loop broken at an "ideal" point:

$$T_v \equiv \frac{v_y}{v_x} = T$$

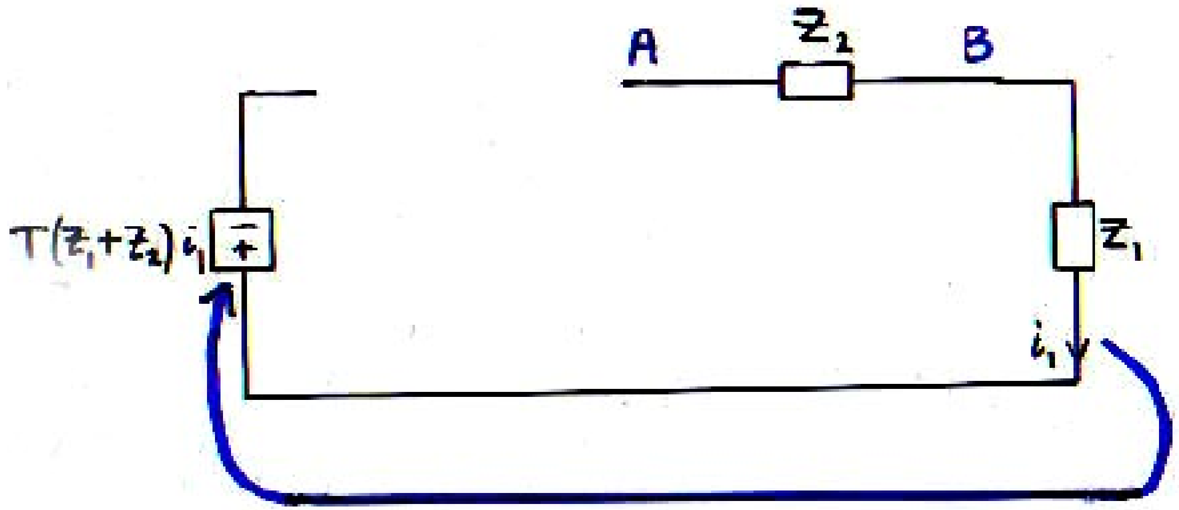


Same results

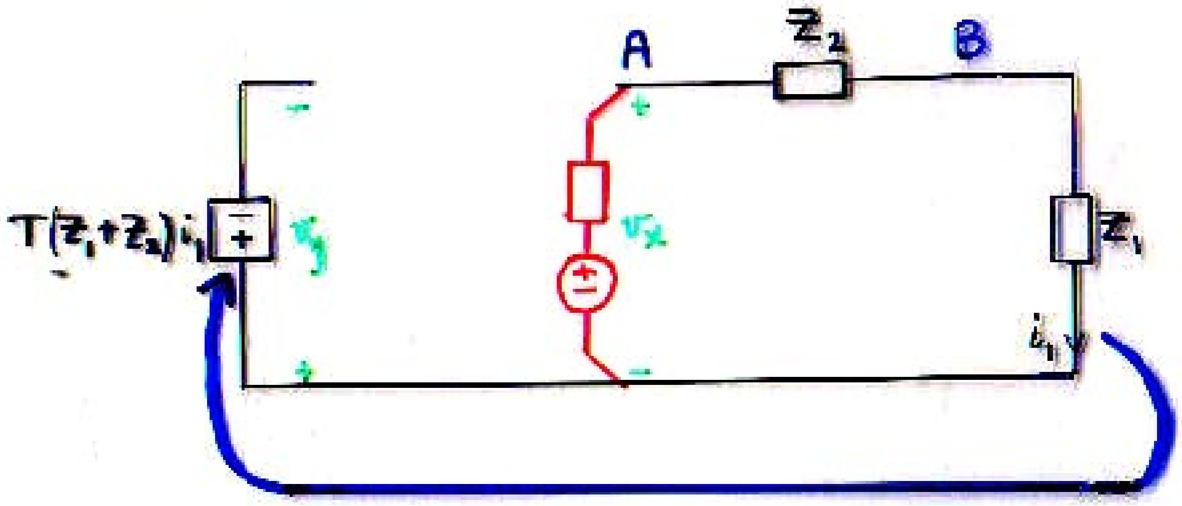
Loop gain by application of a test signal to the loop broken at an "ideal" point:

$$T_v \equiv \frac{v_y}{v_x} = T$$

Redraw the model:



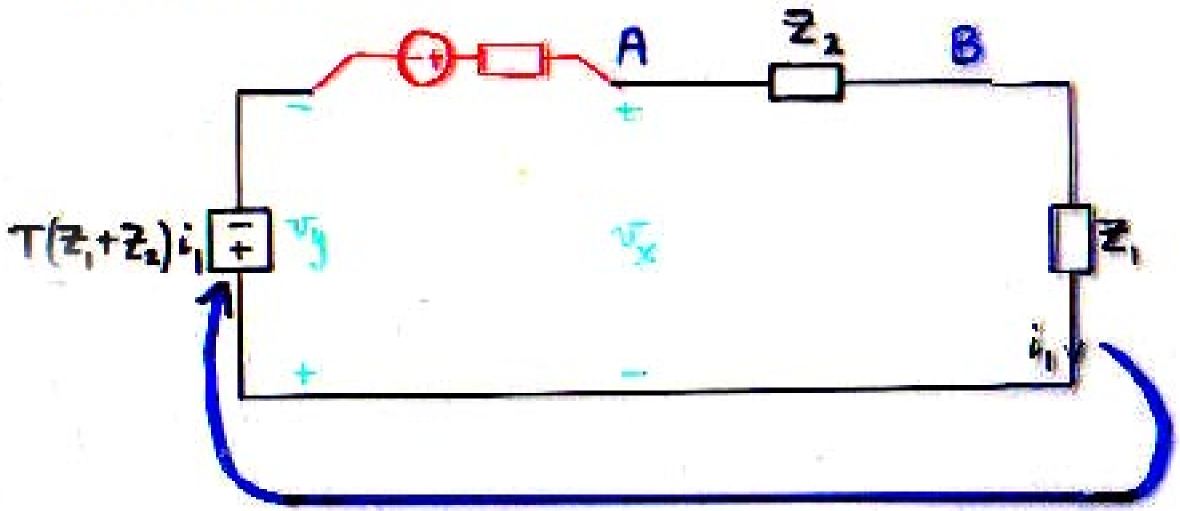
Redraw the model:



Loop gain by application of a test signal to the loop broken at an "ideal" point:

$T_v \equiv \frac{v_y}{v_x} = T$

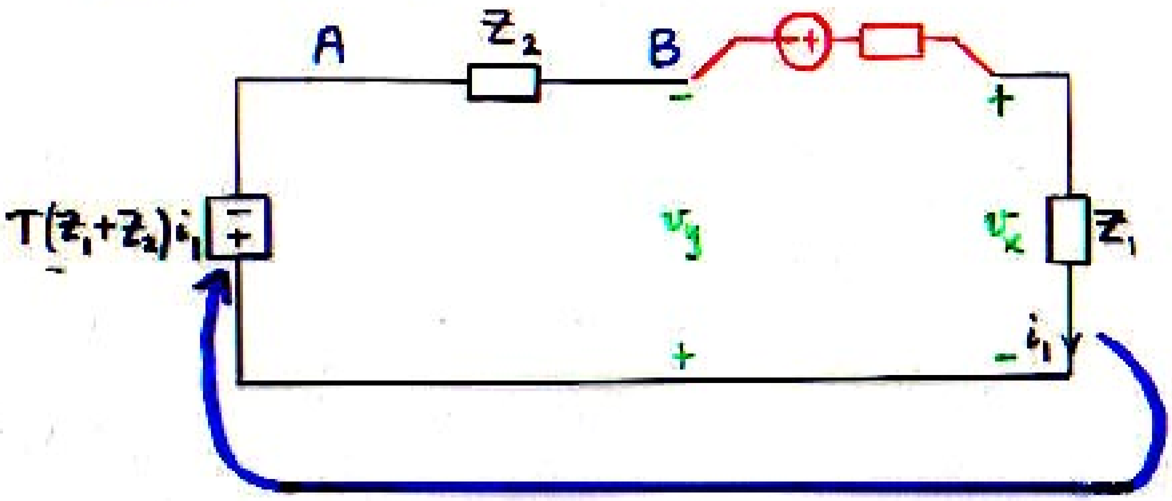
Redraw the model:



Loop gain by injection of a test signal at an "ideal" point:

$$T_v \equiv \frac{v_y}{v_x} = T \quad \leftarrow \quad \begin{cases} v_y = T Z i_1 \\ i_1 = \dfrac{v_x}{Z} \end{cases}$$

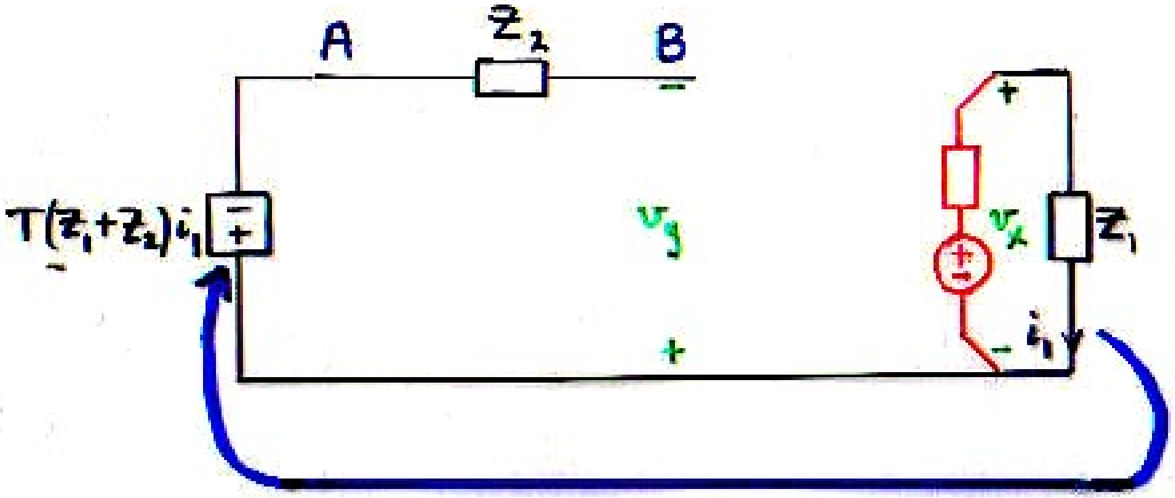
Redraw the model:



However, results are different if test signal is injected at "nonideal" point B:

$$T_v = \frac{v_y}{v_x} = \left(1 + \frac{Z_2}{Z_1}\right)T + \frac{Z_2}{Z_1} \quad \leftarrow \quad \begin{cases} v_y = T(Z_1+Z_2)i_1 + Z_2 i_1 \\ i_1 = \dfrac{v_x}{Z_1} \end{cases}$$

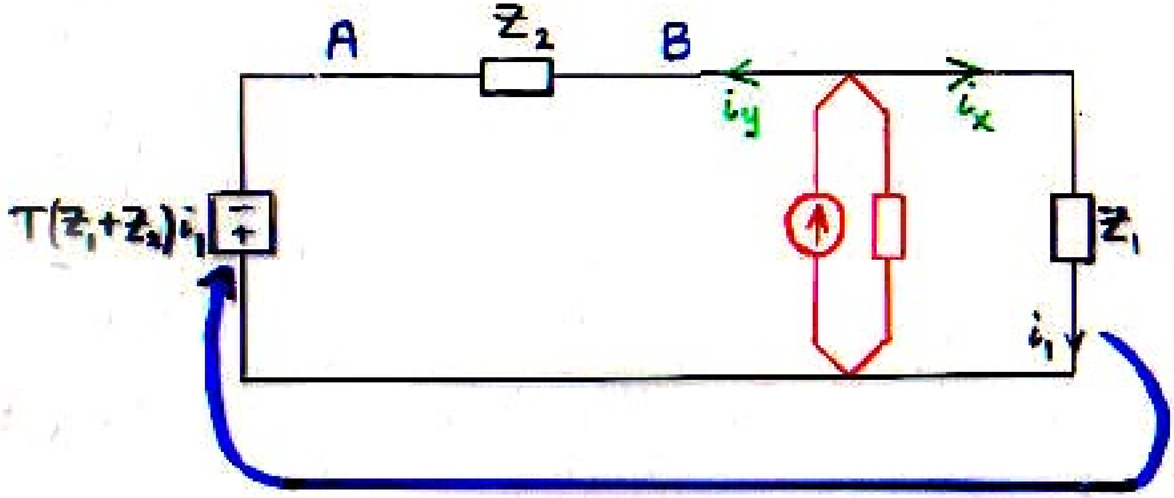
Redraw the model:



Results are different again if test signal is applied to loop broken at "non ideal" point B:

$$T_v \equiv \frac{v_y}{v_x} = \left(1+\frac{Z_2}{Z_1}\right)T \quad \longleftarrow \quad \begin{cases} v_y = T(Z_1+Z_2)i_1 \\ i_1 = \dfrac{v_x}{Z_1} \end{cases}$$

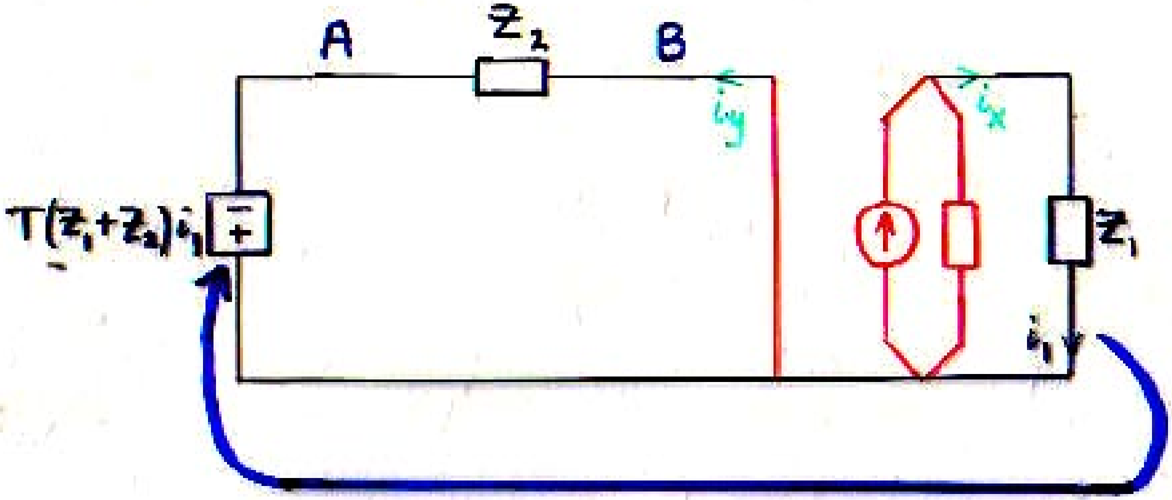
Redraw the model:



If current test signal is injected at the "nonideal" point B:

$$T_i \equiv \frac{i_y}{i_x} = \left(1+\frac{Z_1}{Z_2}\right)T + \frac{Z_1}{Z_2} \quad \leftarrow \quad \begin{cases} i_y = \dfrac{T(Z_1+Z_2)\,i_1 + Z_1 i_1}{Z_2} \\ i_1 = i_x \end{cases}$$

Redraw the model:



If a current test signal is applied to loop broken (shorted) at the "nonideal" point B:

$$T_i \equiv \frac{i_y}{i_x} = \left(1 + \frac{Z_1}{Z_2}\right) T \quad \Leftarrow \quad \begin{cases} i_y = \dfrac{T(Z_1+Z_2)}{Z_2} \\ i_1 = i_x \end{cases}$$

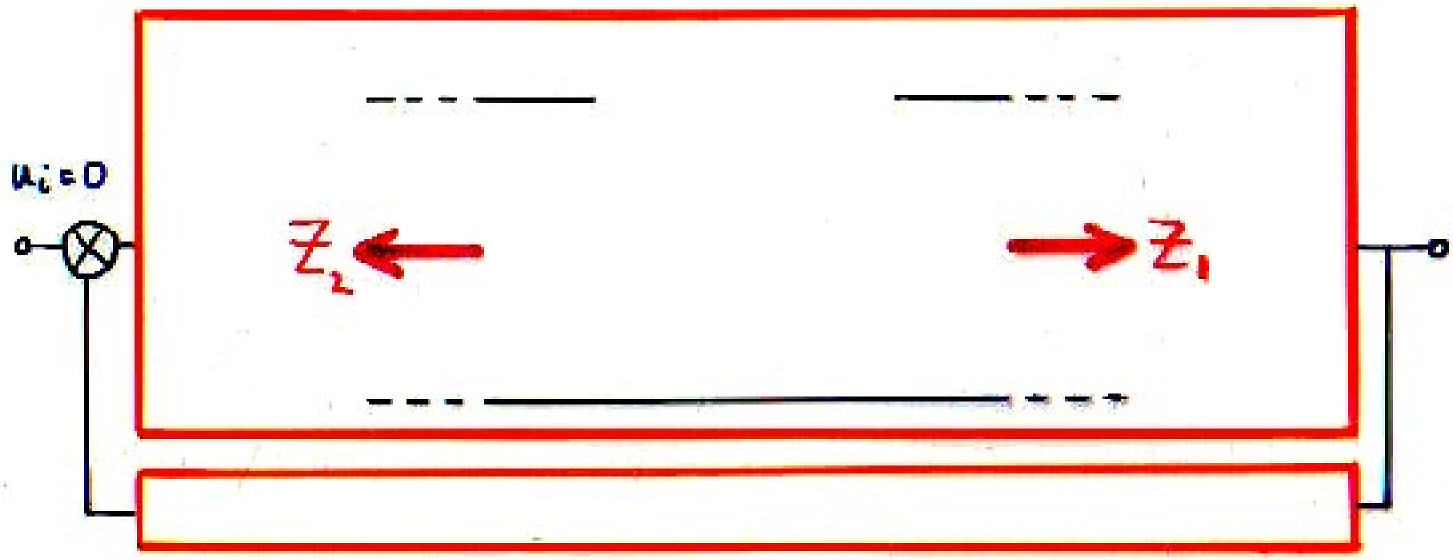
Loop gain T can be calculated or measured by

1. Test signal applied to broken loop
2. Test signal injected into the closed loop.

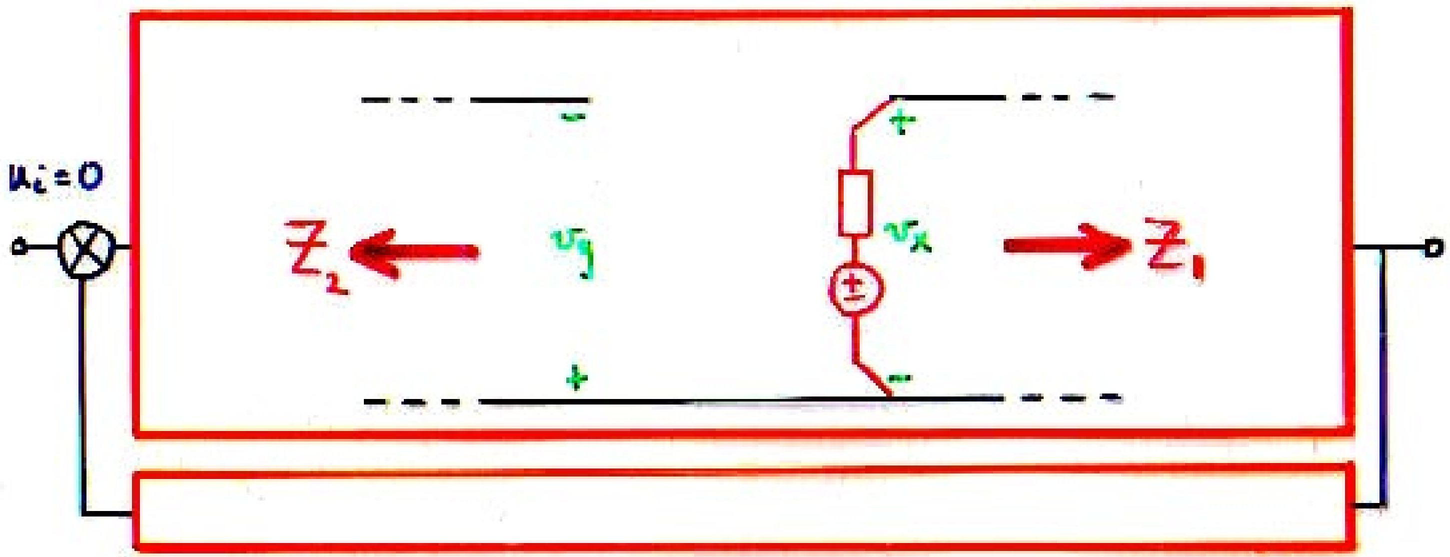
Method 2 is preferable for measurement, since the loop remains closed and the dc operating points remain undisturbed. If method 1 is used for measurement, a dc bias must be applied to re-establish the proper operating point before the ac test signal can be applied.

In either method, certain inequalities must be satisfied by the impedance ratio Z_2/Z_1, where

$$\frac{Z_2}{Z_1} = \left.\frac{\text{impedance looking back}}{\text{impedance looking forward}}\right\} \begin{array}{l}\text{into the loop from} \\ \text{the injection point}\end{array}$$



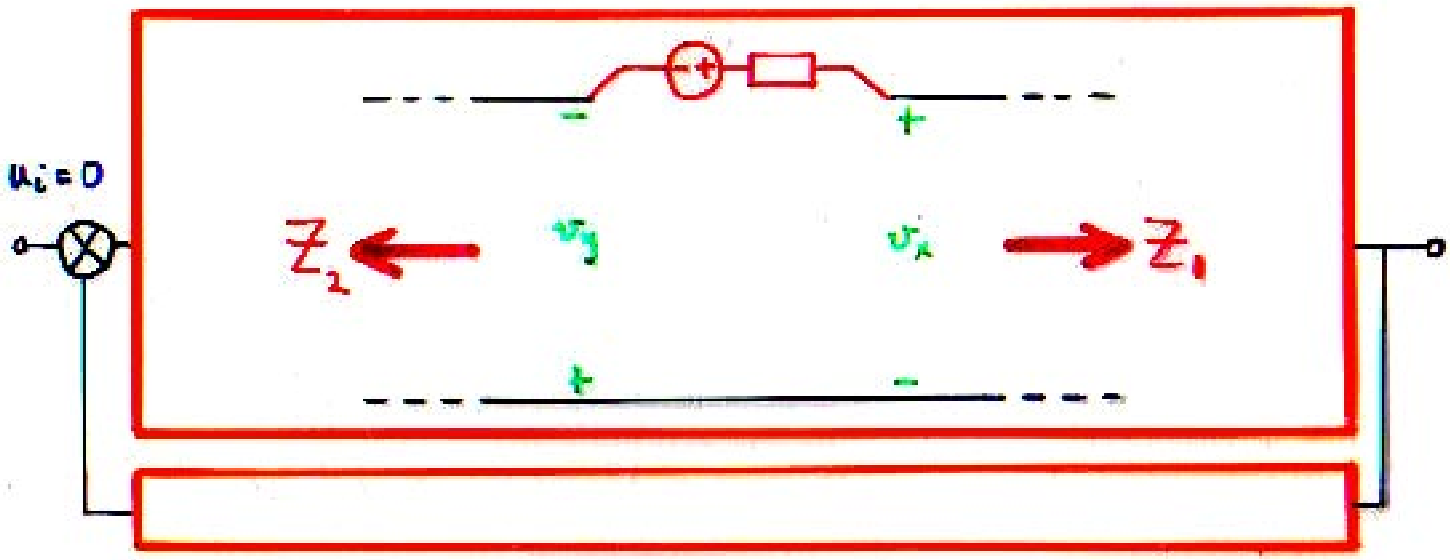
$u_i = 0$
Z_2
Z_1



Voltage test signal applied to broken loop:

$$T_v = \frac{v_y}{v_x} = \left(1 + \frac{Z_2}{Z_1}\right) T$$

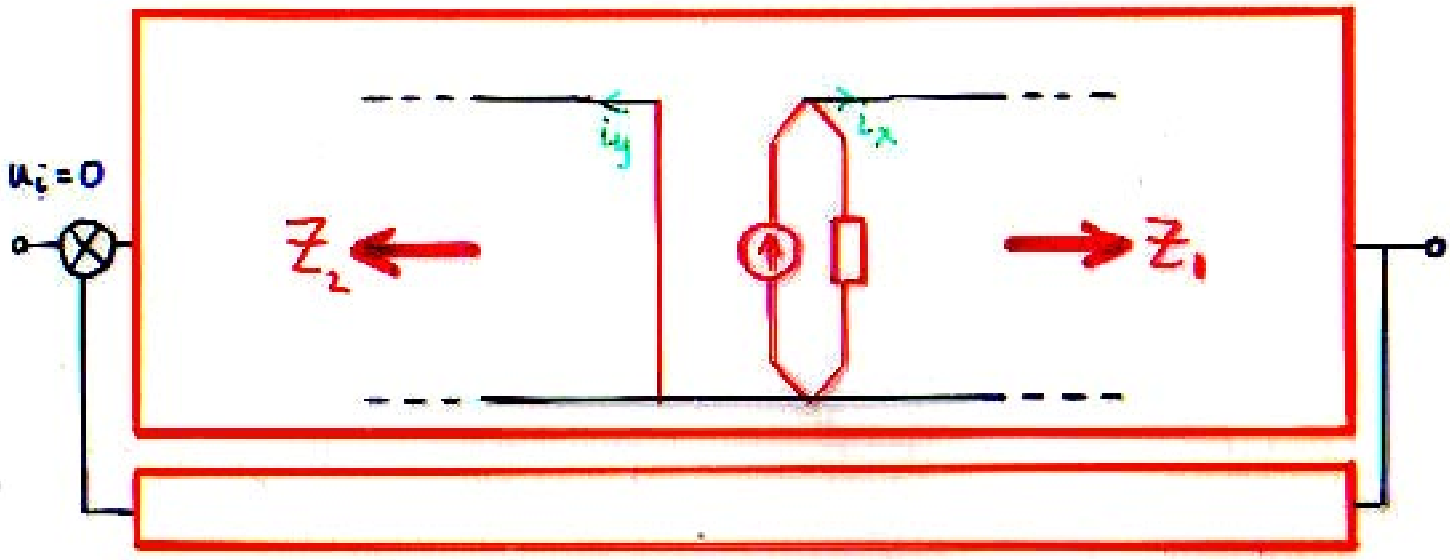
$$\rightarrow T \quad \text{if} \quad \frac{Z_2}{Z_1} \ll 1$$



Voltage test signal injected into closed loop:

$$T_v \equiv \frac{v_y}{v_x} = \left(1 + \frac{Z_2}{Z_1}\right)T + \frac{Z_2}{Z_1}$$

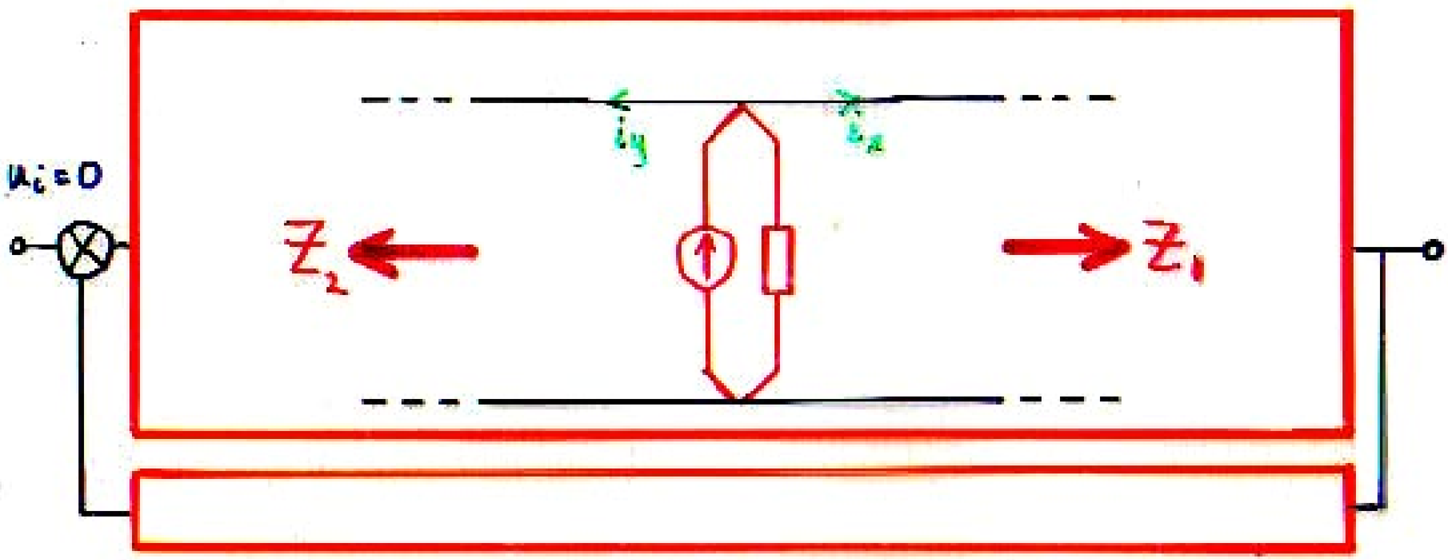
$$\rightarrow T \quad \text{if} \quad \frac{Z_2}{Z_1} \ll 1 \ \underline{\text{and}} \ \frac{Z_2}{Z_1} \ll T$$



Current test signal applied to broken loop:

$$T_i = \frac{i_y}{i_x} = \left(1 + \frac{Z_1}{Z_2}\right) T$$

$$\rightarrow T \quad \text{if} \quad \frac{Z_1}{Z_2} \ll 1$$



Current test signal injected into closed loop:

$$T_i \equiv \frac{i_y}{i_x} = \left(1 + \frac{Z_1}{Z_2}\right) T + \frac{Z_1}{Z_2}$$

$$\rightarrow T \quad \text{if} \quad \frac{Z_1}{Z_2} \ll 1 \text{ and } \frac{Z_1}{Z_2} \ll T$$

Generalization: Determination of loop gain by voltage/current application/injection at an ideal/nonideal point

$$Z\text{-ratio} \equiv \begin{cases} \dfrac{Z_2}{Z_1} & \text{for voltage application/injection} \\ \dfrac{Z_1}{Z_2} & \text{for current application/injection} \end{cases}$$

where

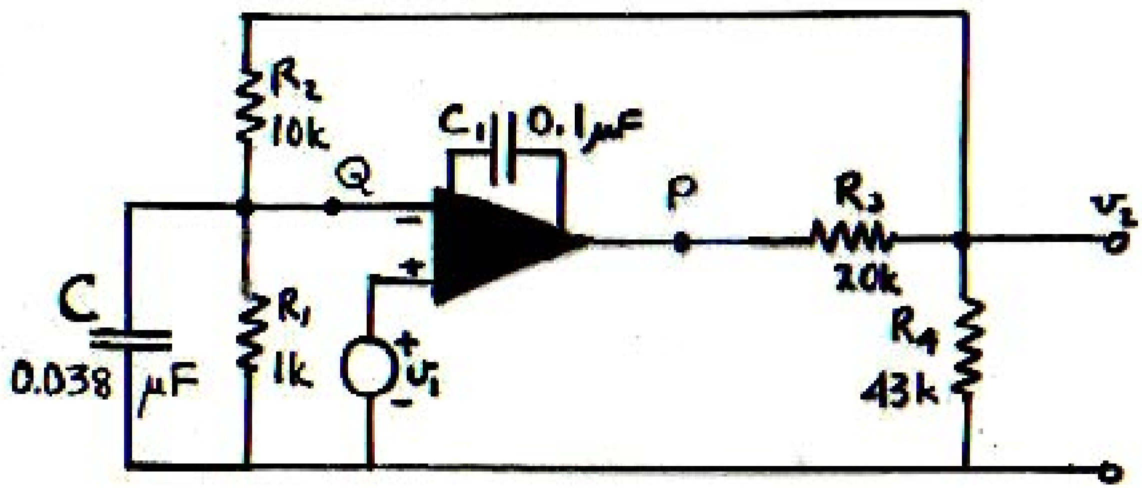
$Z_1 \equiv$ impedance looking forward from application/injection point
$Z_2 \equiv$ " " backward " " " "

To determine loop gain, both by signal application to a broken loop and by signal injection into a closed loop, the Z-ratio must be sufficiently small; the necessary inequalities are different:

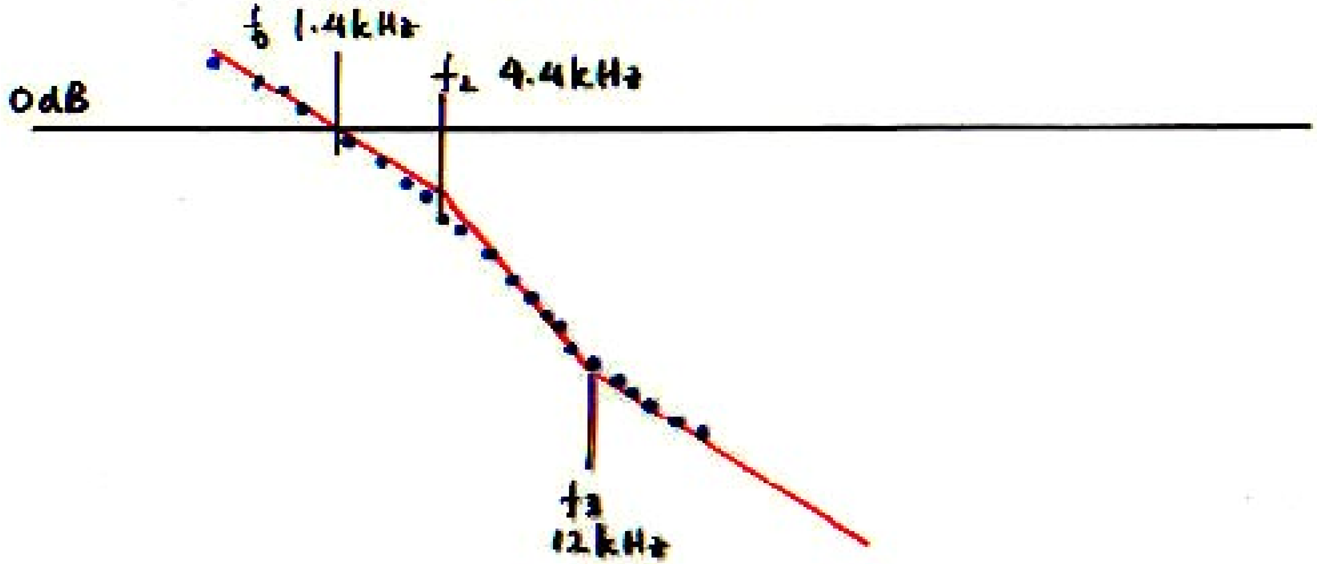
For signal application to a broken loop: $Z\text{-ratio} \ll 1$
For signal injection into a closed loop: $Z\text{-ratio} \ll 1$ and $\ll T$

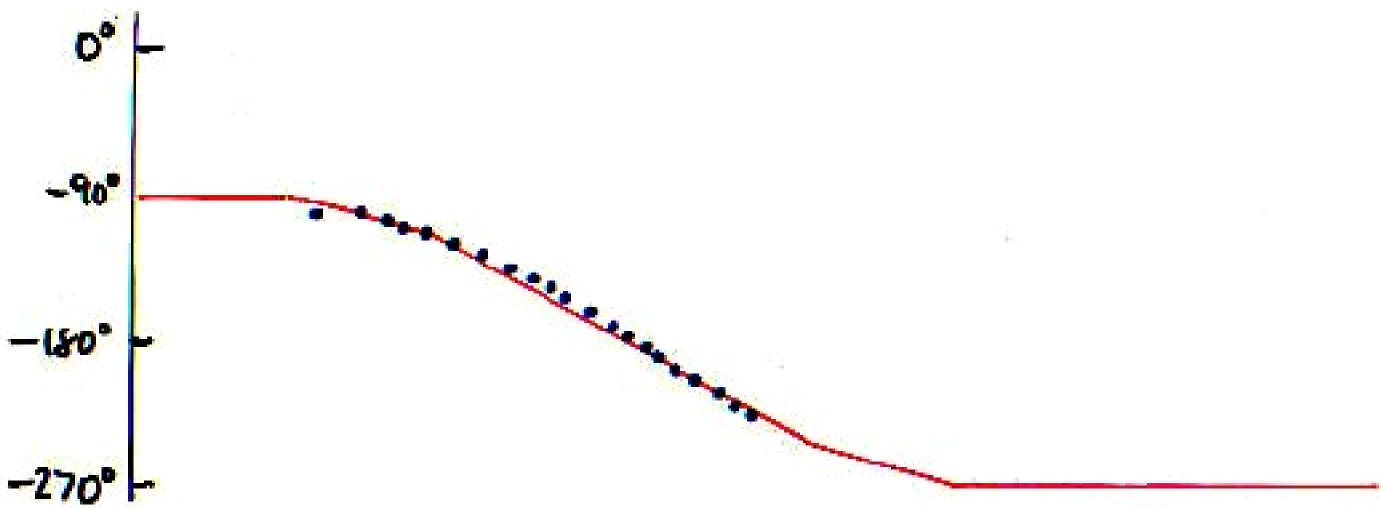
The impedance of the signal source is irrelevant in all cases.

Example



Example of T_v not being equal to T: the previous opamp circuit at high frequencies.





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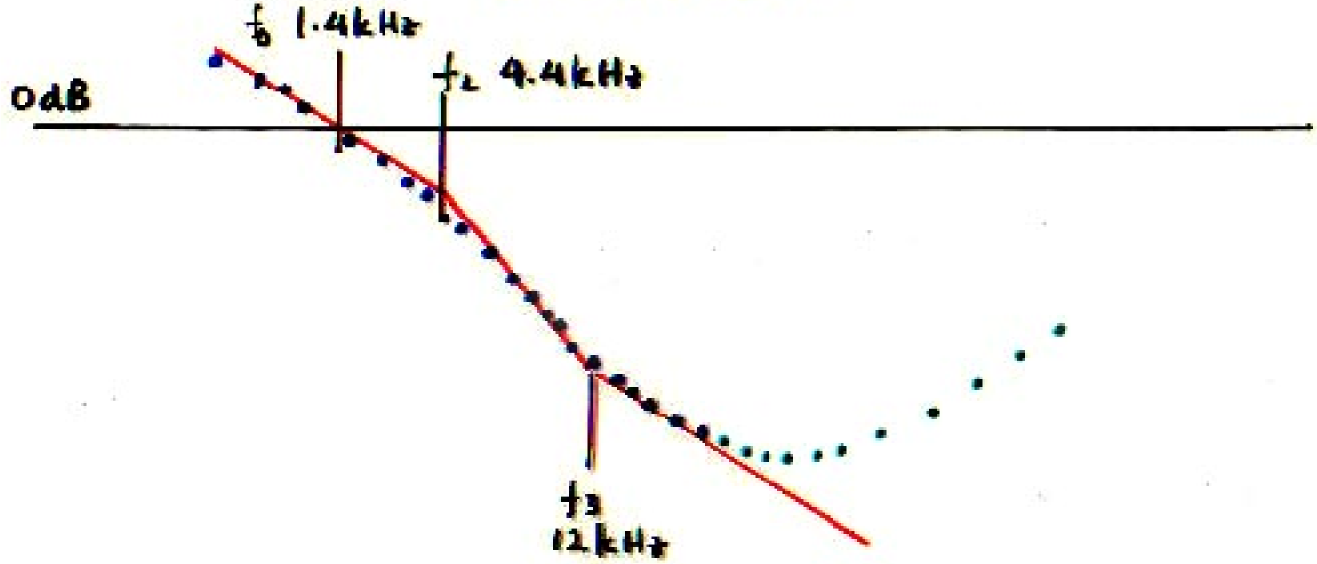
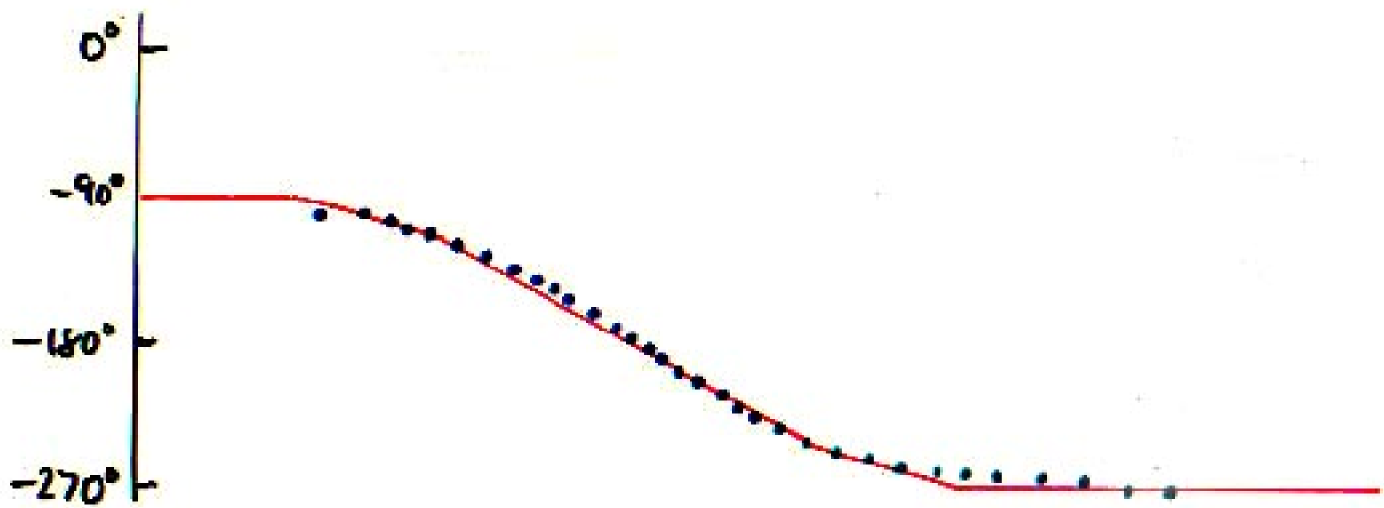
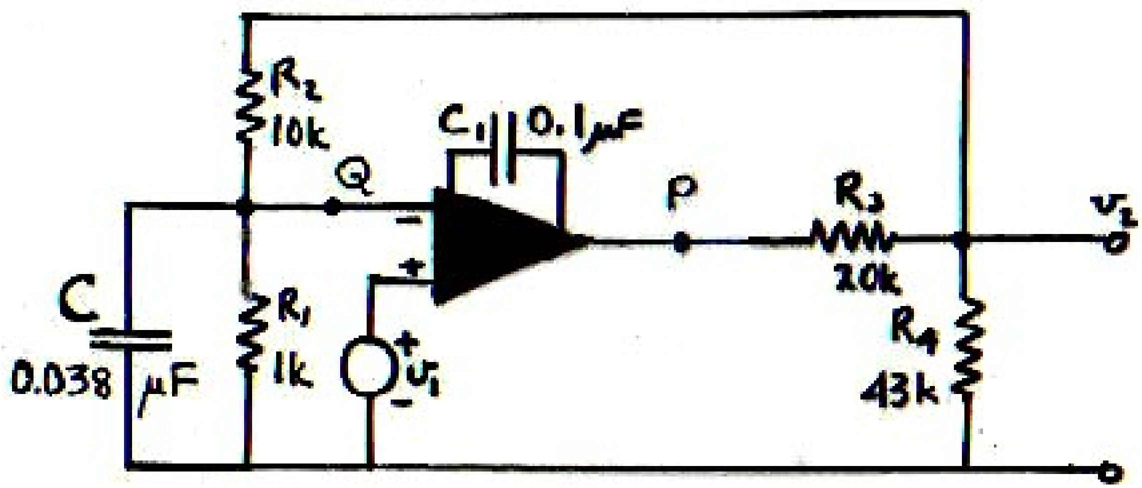
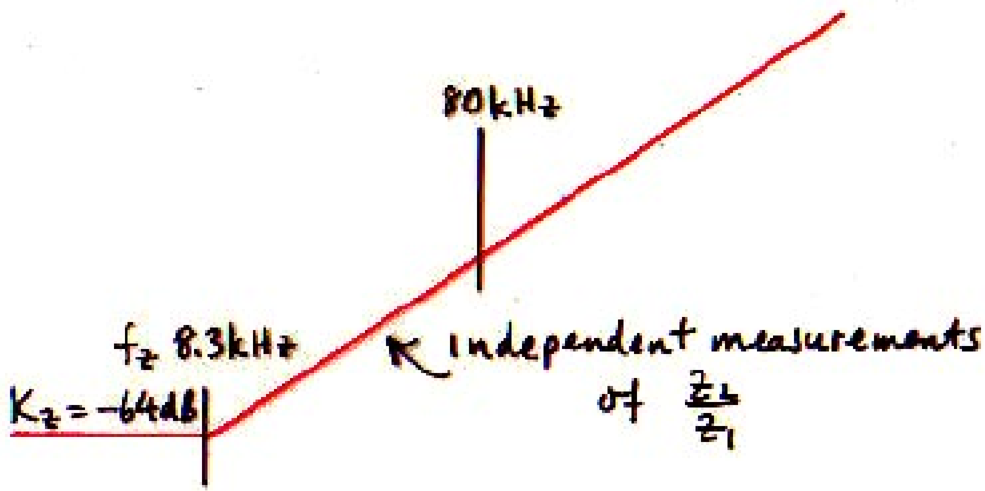




Example




80kHz
fz 8.3kHz
Kz = -64dB
independent measurements of Z2/Z1

Analytically:

$$T_v = \left(1 + \frac{Z_2}{Z_1}\right)T + \frac{Z_2}{Z_1} \approx T + \frac{Z_2}{Z_1}$$

$$= \frac{1 - \frac{s}{\omega_3}}{\frac{s}{\omega_0}\left(1 + \frac{s}{\omega_2}\right)} + K_z\left(1 + \frac{s}{\omega_z}\right)$$

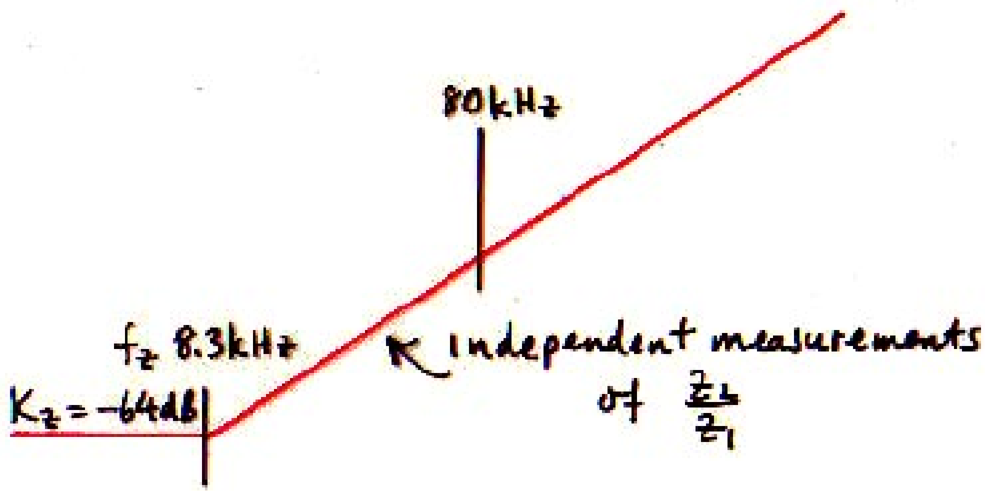
In the neighborhood of the crossover:

$$T_v = \frac{-\frac{s}{\omega_3}}{\frac{s}{\omega_0} \cdot \frac{s}{\omega_2}} + K_z \frac{s}{\omega_z}$$

$$= \frac{-\frac{s}{\omega_3}\left[1 - \left(\frac{s}{\omega_c}\right)^2\right]}{\frac{s}{\omega_0} \cdot \frac{s}{\omega_2}}$$

where

$$\omega_c \equiv \sqrt{\frac{\omega_0 \omega_2 \omega_z}{K_z \omega_3}} \qquad f_c = 81\,\text{kHz}$$



80kHz
f_z 8.3kHz
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$K_z = -64dB$

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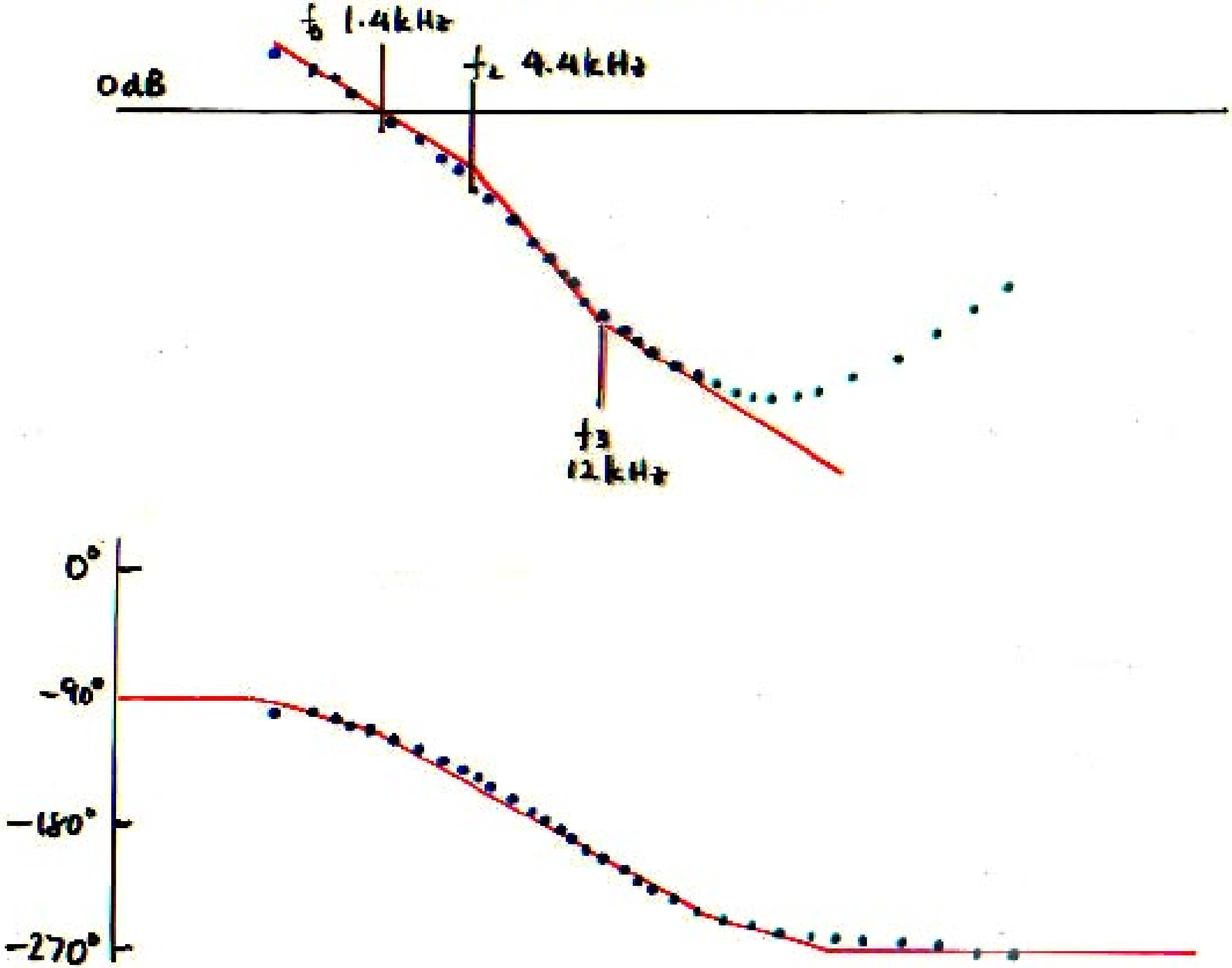

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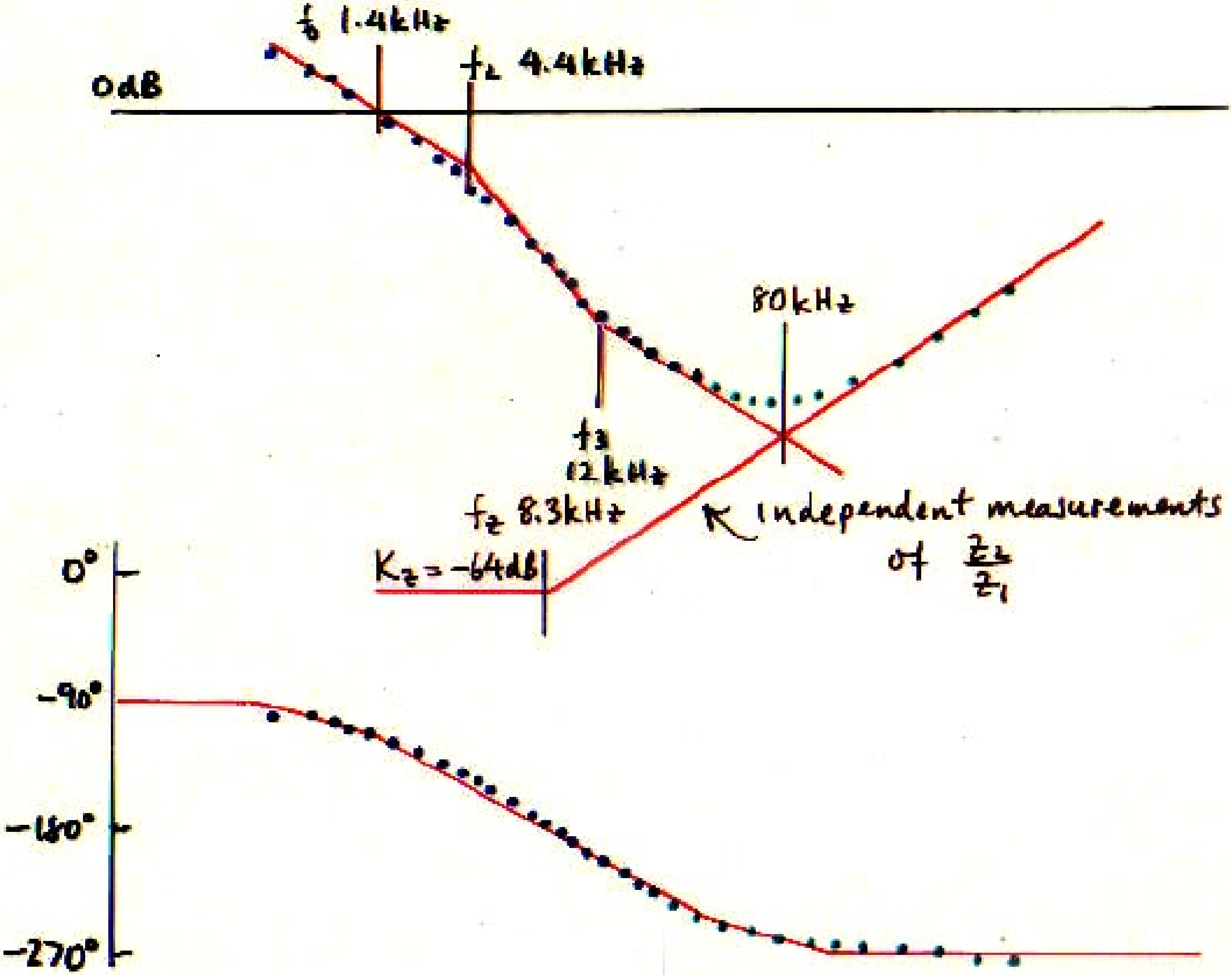

Analytically:

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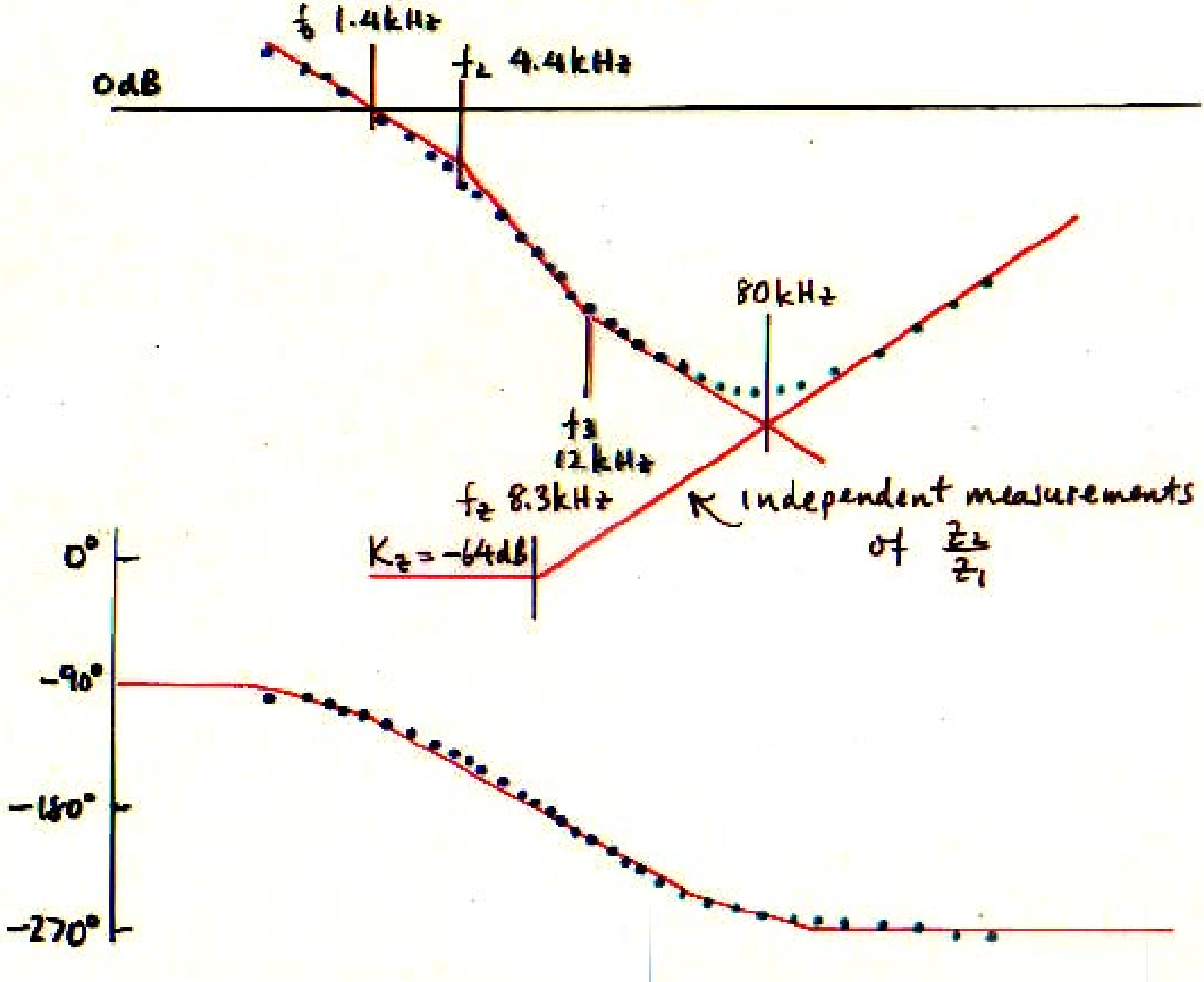

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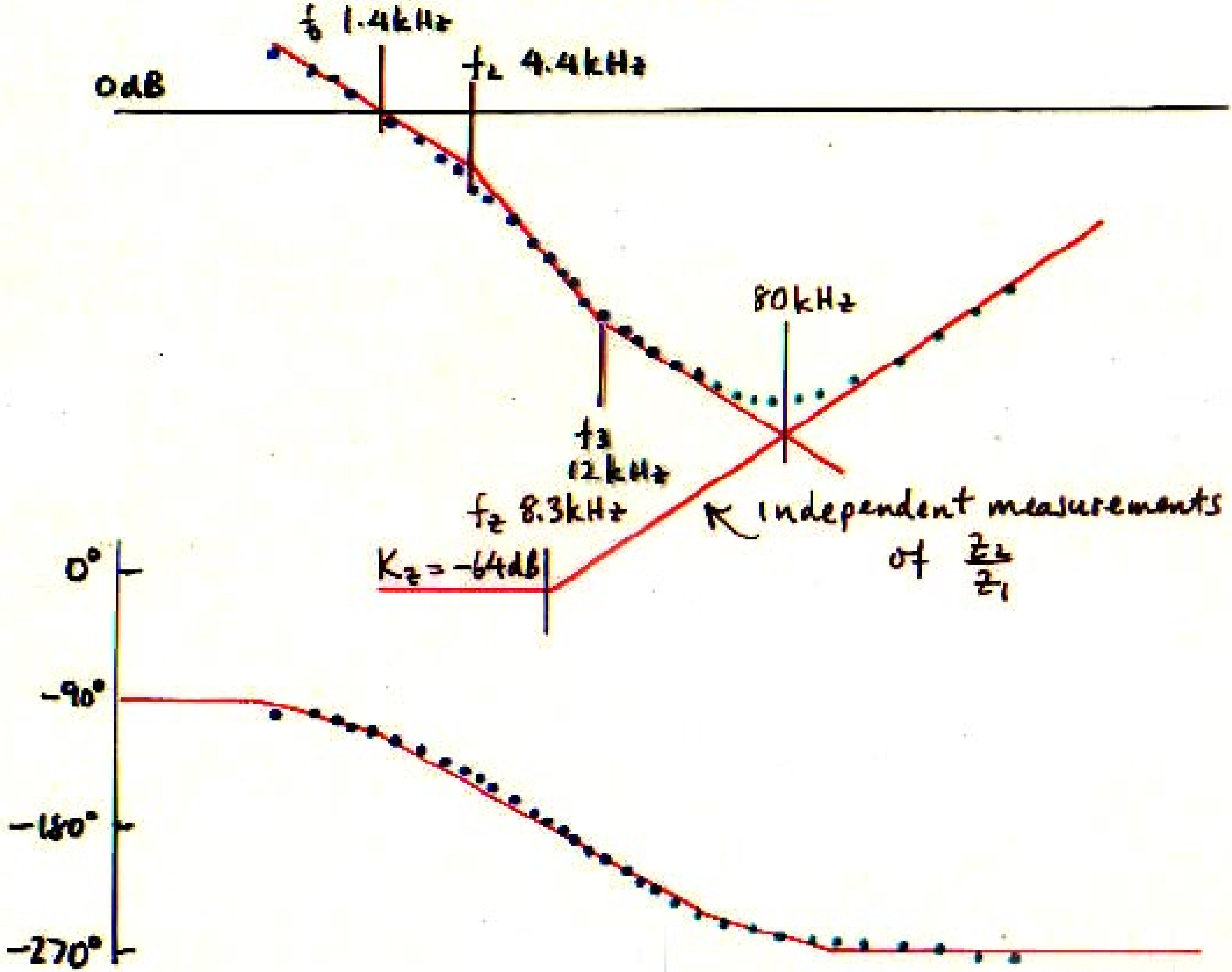

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$$= \frac{1-\frac{s}{\omega_3}}{\frac{s}{\omega_0}\left(1+\frac{s}{\omega_2}\right)} + K_z\left(1+\frac{s}{\omega_z}\right)$$

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where

$$\omega_c \equiv \sqrt{\frac{\omega_0\,\omega_2\,\omega_z}{K_z\,\omega_3}} \qquad f_c = 81\ \text{kHz}$$

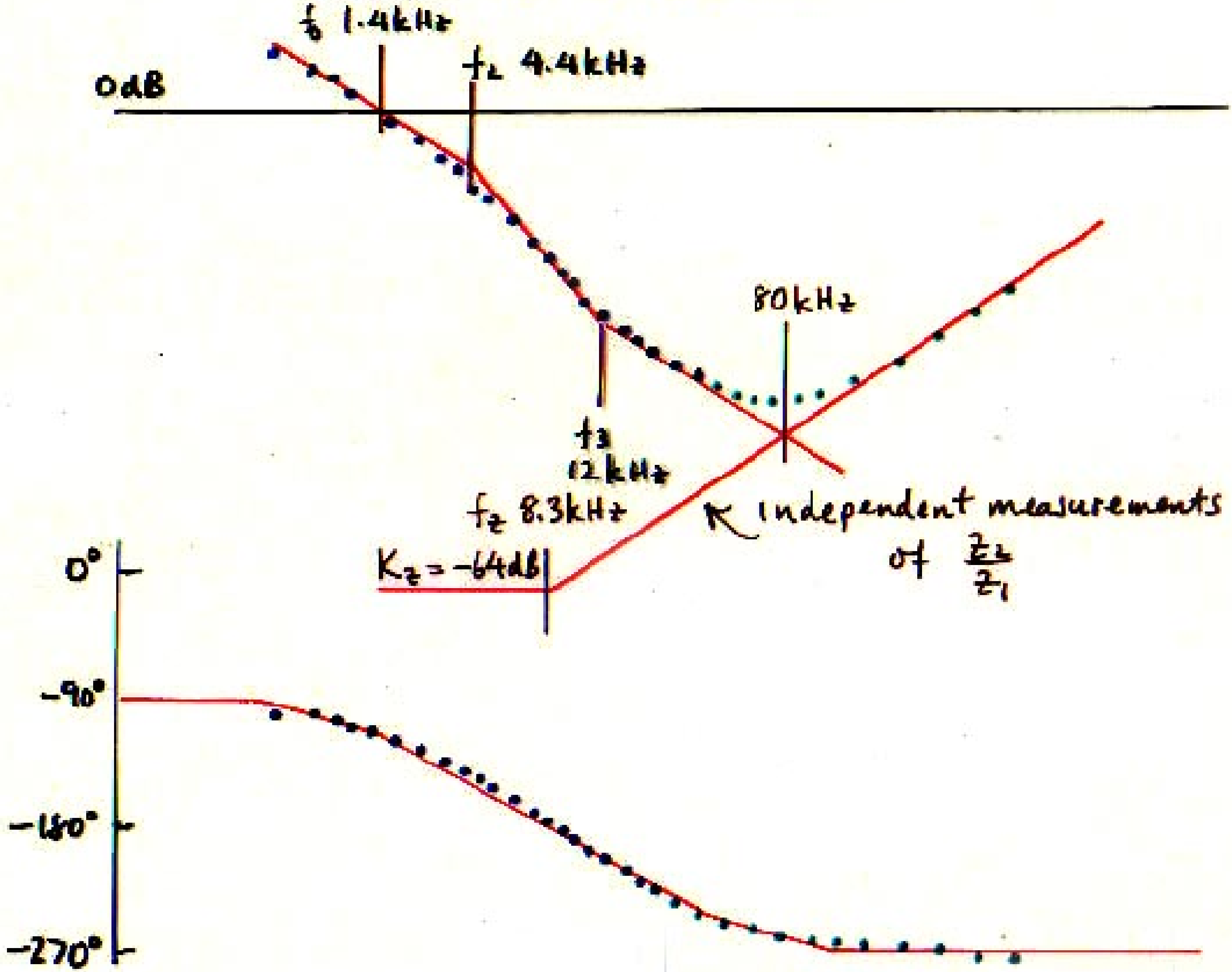
Hence, over the entire frequency range:

$$T_v = \frac{\left(1-\frac{s}{\omega_3}\right)\left(1+\frac{s}{\omega_c}\right)\left(1-\frac{s}{\omega_c}\right)}{\frac{s}{\omega_0}\left(1+\frac{s}{\omega_2}\right)}$$

This is the same as the original T multiplied by a correction factor having a lhp and a rhp zero at the same frequency. This causes the change of magnitude slope from the original, without a change of phase asymptote.

Hence, the true T is as previously determined, but the deviation of the measured T_v at high frequencies results from Z_2/Z_1 no longer being small compared to T.

Example of T_v not being equal to T: the previous opamp circuit at high frequencies.



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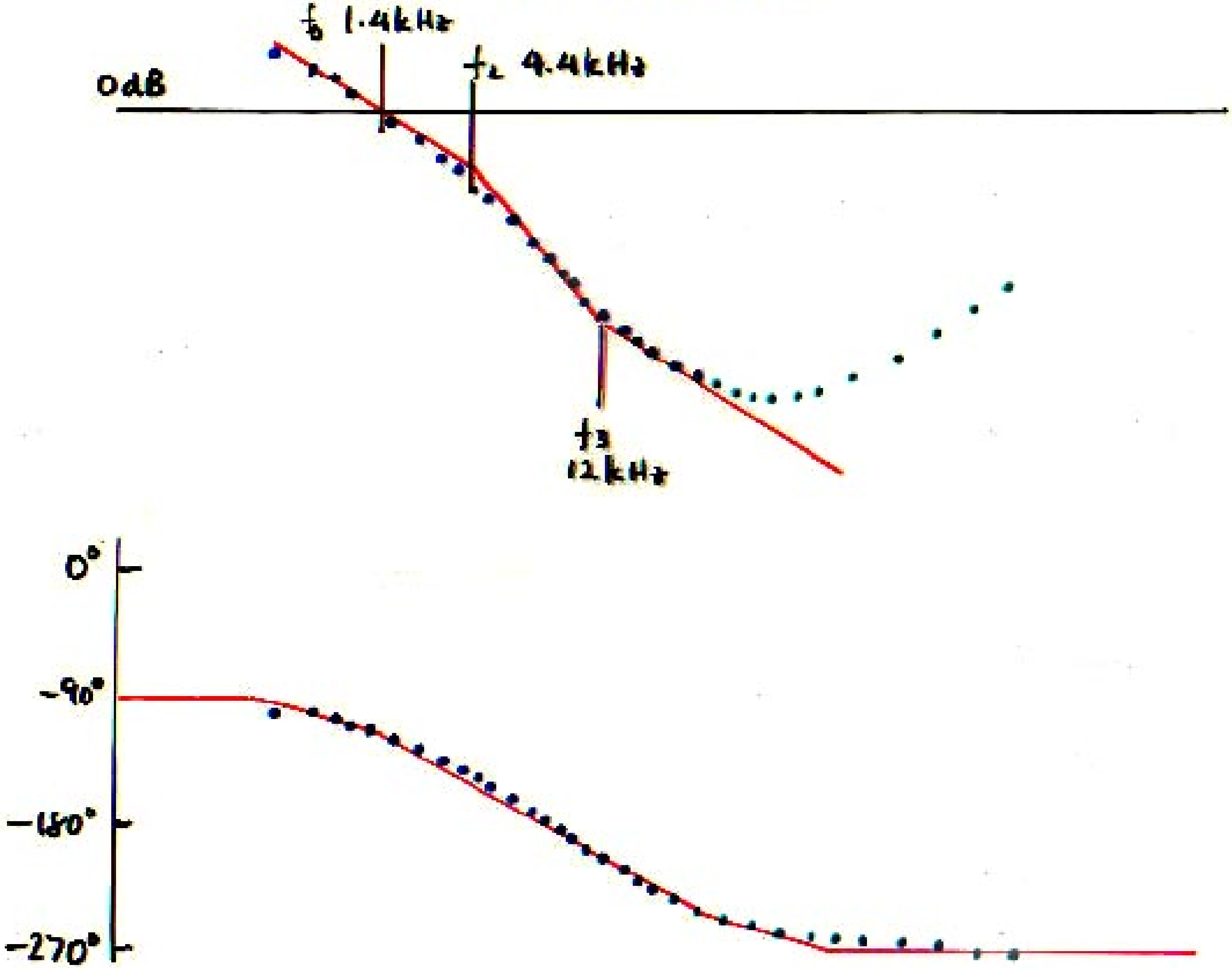


Generalization: Loop Gain Test Signal Injection at a Nonideal Point

In order to satisfy the requirement that injection of the test signal should add to the forward signal without affecting the loading, the following conditions are required, where Z_1 is the impedance looking "forward" from the injection point, and Z_2 is the impedance looking "backwards" from the injection point:

1. For series voltage injection:

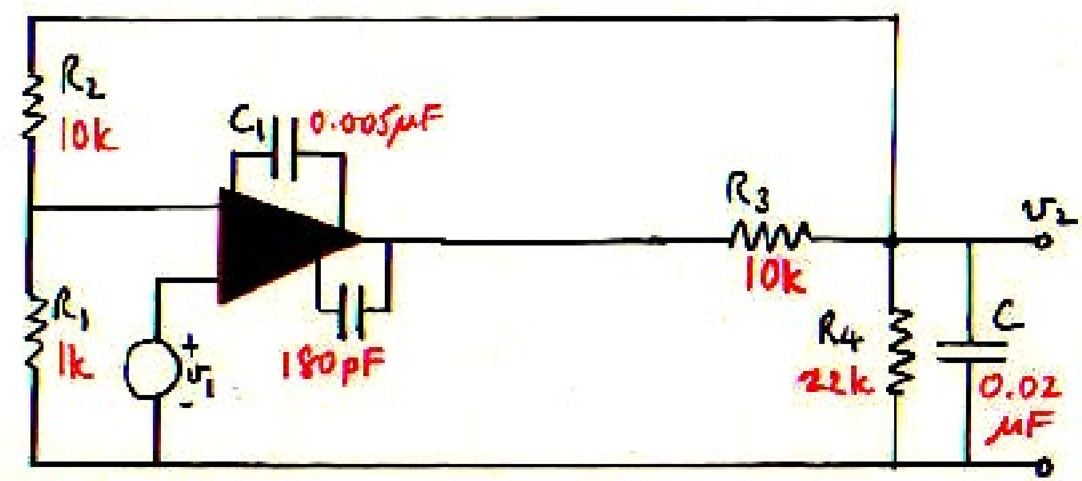
$$\frac{Z_2}{Z_1} \ll 1, \qquad \frac{Z_2}{Z_1} \ll T$$

2. For shunt current injection:

$$\frac{Z_1}{Z_2} \ll 1, \qquad \frac{Z_1}{Z_2} \ll T$$

Measurement of an unstable loop gain.

Suppose the following amplifier has been designed:



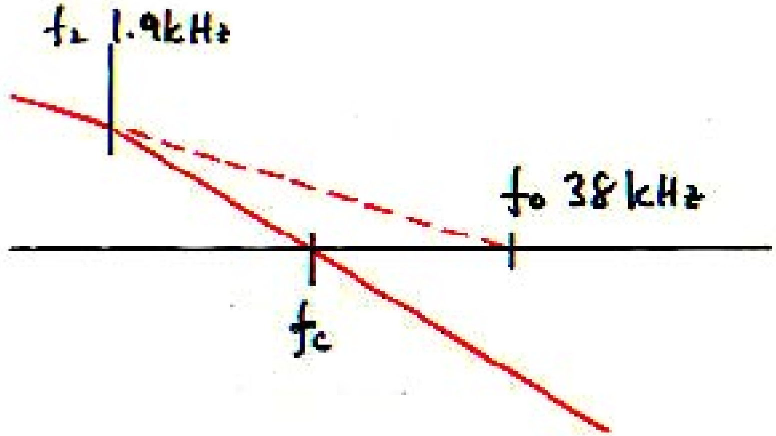
Predicted loop gain: $T = A_1 A_2 K_0 \dfrac{1}{1+\frac{s}{\omega_2}}$

where $A_1 = \dfrac{\omega_a}{s}$, $f_a = 1\,MHz$ $\quad A_2K_0 = \dfrac{R_4\|(R_1+R_2)}{R_3+R_4\|(R_1+R_2)}\,\dfrac{R_1}{R_1+R_2} = 0.038$

$$\omega_2 = \frac{1}{C[R_3\|R_4\|(R_1+R_2)]} \qquad f_2 = 1.9\,kHz$$

Hence $$T = \frac{1}{\frac{s}{\omega_0}\left(1+\frac{s}{\omega_2}\right)}$$

where $\omega_0 = A_2K_0\omega_a$ $\quad f_0 = 0.038 \times 1 = 38\,kHz$



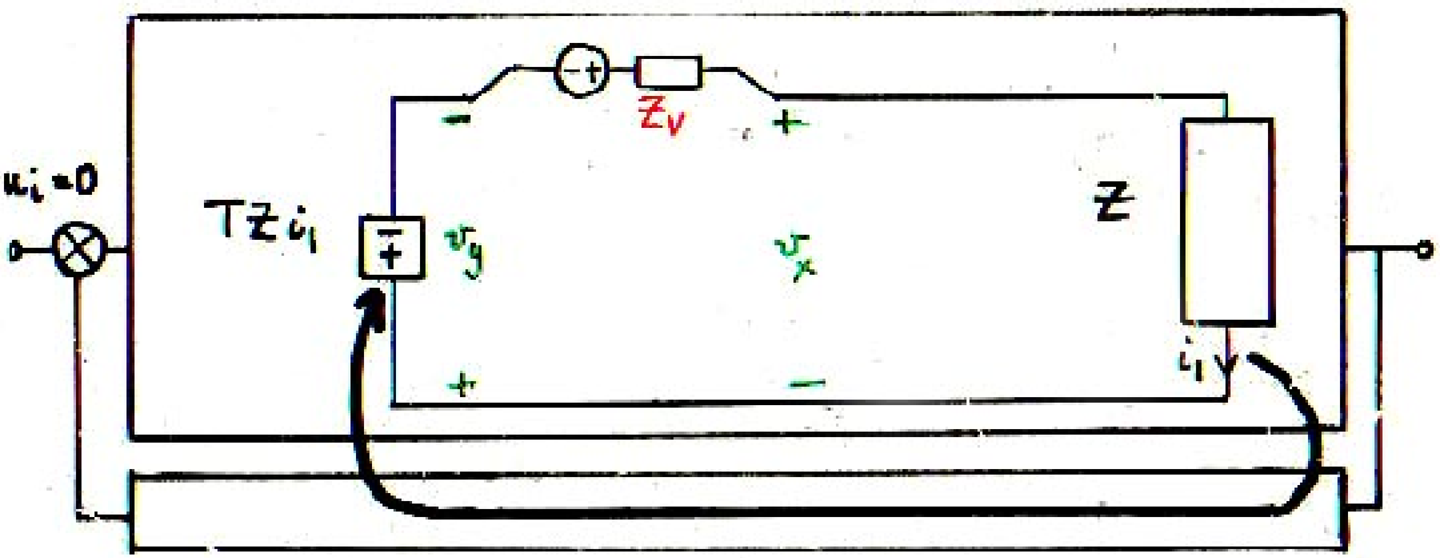
The Q of the quadratic in $T/(1+T)$ is

$$Q = \sqrt{\frac{\omega_0}{\omega_2}} = \sqrt{\frac{38}{1.9}} = 4.5 \Rightarrow 13\,dB$$

Hence $\phi_M = 14°$

Since f_c is far from f_2, the actual crossover frequency is essentially f_c, so ϕ_M can be checked directly from:

$$\phi_M = 180 + \angle T\big|_{f=f_c} =$$



Loop gain by injection of a test signal at an "ideal" point:

$$T_v \equiv \frac{v_y}{v_x} = T \quad \leftarrow \quad \begin{cases} v_y = TZi_1 \\ i_1 = \dfrac{v_x}{Z} \end{cases}$$

regardless of Z_V

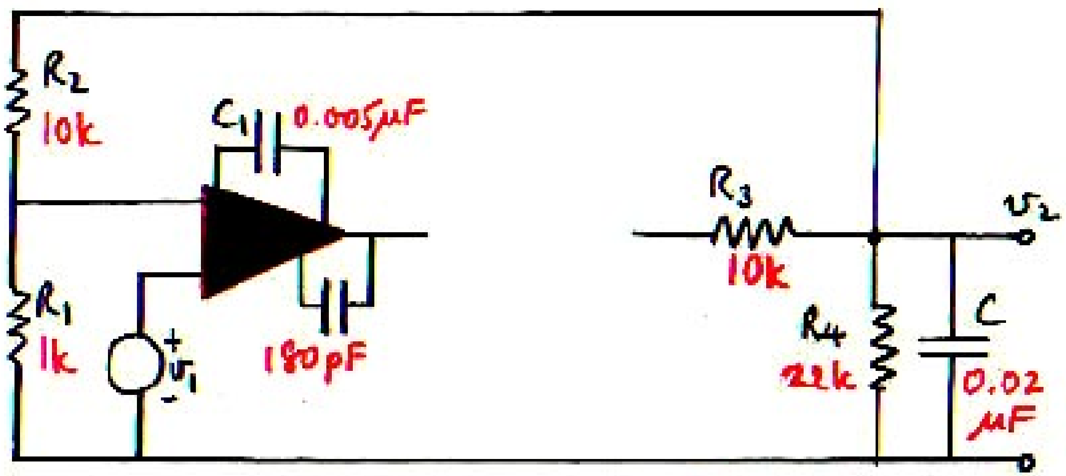
However, the actual circuit is unstable.

Objective: find a way to stop the oscillation without changing the measurement of the original unstable T.

Solution: Insert a sufficient impedance Z_v in series with the injected voltage source that is to be used to measure T. As already seen, this impedance Z_v does not affect the measurement of T, but can be made large enough to stop the oscillation.

Measurement of an unstable loop gain.

Suppose the following amplifier has been designed:



Predicted loop gain: $T = A_1 A_2 K_0 \dfrac{1}{1+\frac{s}{\omega_2}}$

where $A_1 = \dfrac{\omega_a}{s}$, $f_a = 1\,MHz$ $\quad A_2 K_0 = \dfrac{R_4 \| (R_1+R_2)}{R_3 + R_4 \| (R_1+R_2)} \dfrac{R_1}{R_1+R_2} = 0.038$

$$\omega_2 = \frac{1}{C[R_3 \| R_4 \| (R_1+R_2)]} \qquad f_2 = 1.9\,kHz$$

Hence $T = \dfrac{1}{\frac{s}{\omega_0}\left(1+\frac{s}{\omega_2}\right)}$

where $\omega_0 = A_2 K_0 \omega_a$ $\quad f_0 = 0.038 \times 1 = 38\,kHz$

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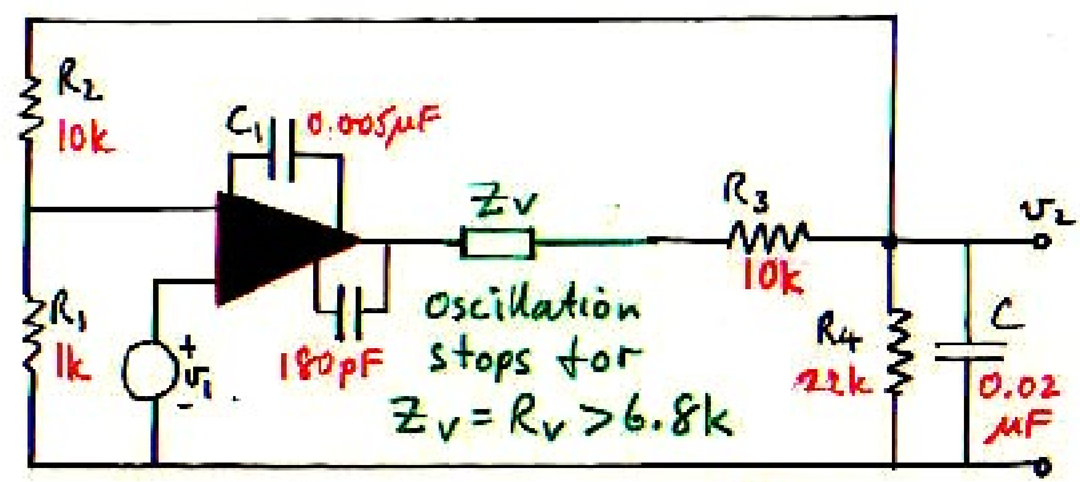

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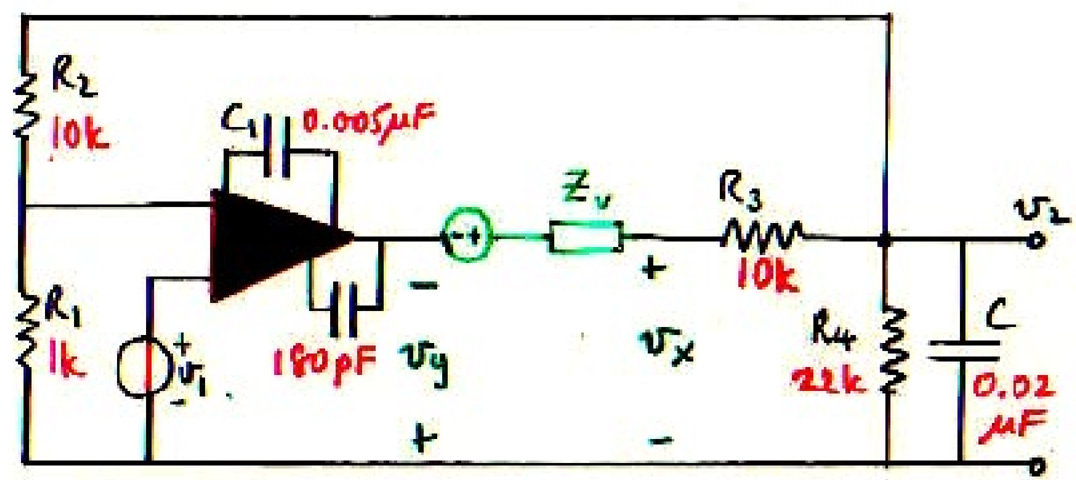

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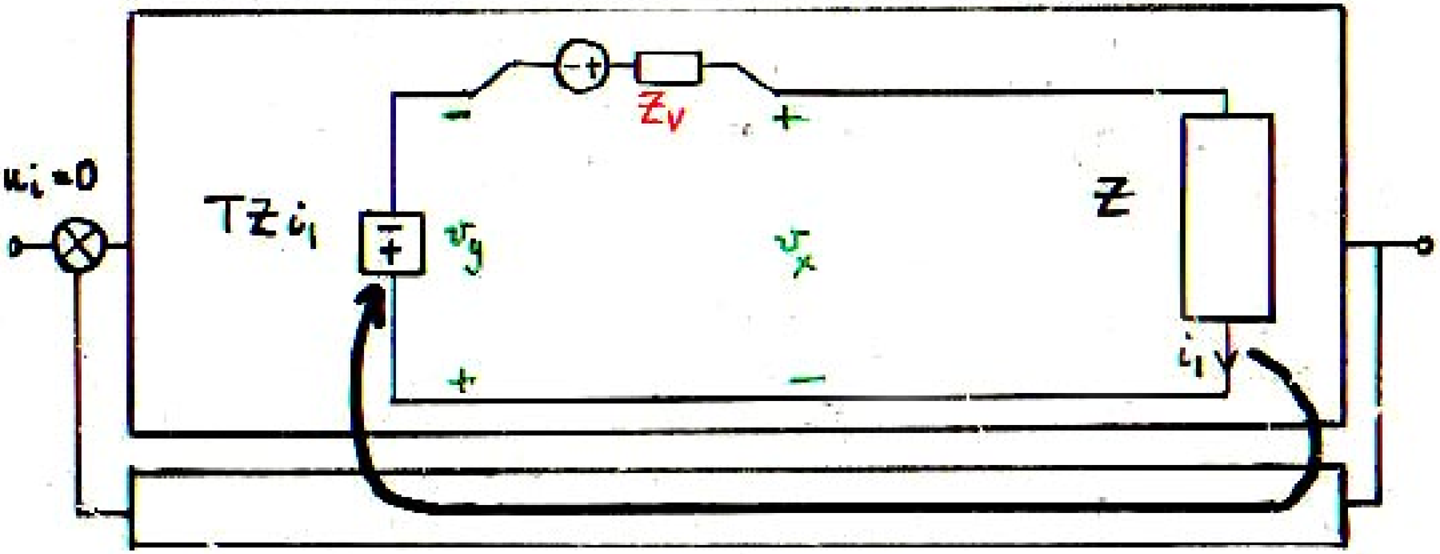

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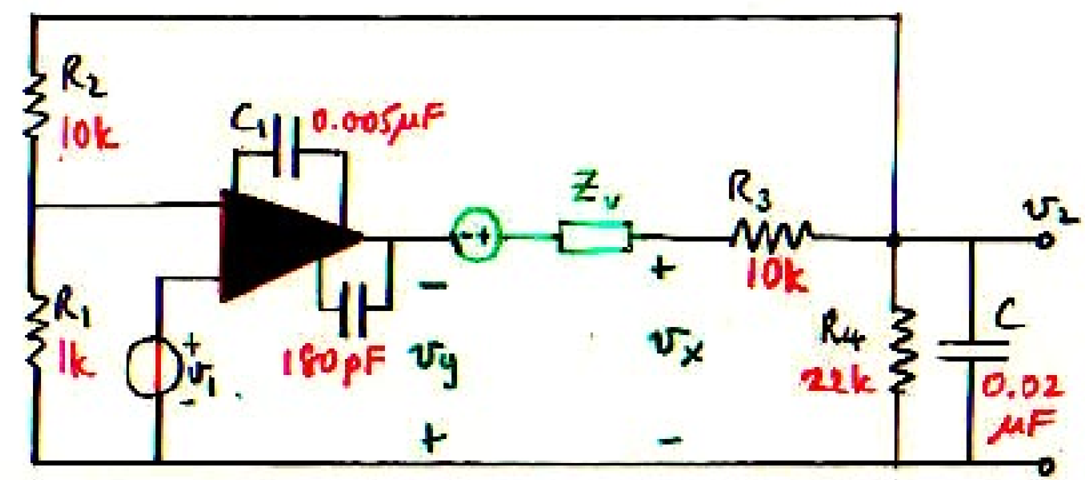

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$\omega_2 = \frac{1}{C[R_3 \| R_4 \| (R_1+R_2)]}$ $\quad f_2 = 1.9kHz$

Hence $T = \frac{1}{\frac{s}{\omega_0}\left(1+\frac{s}{\omega_2}\right)}$

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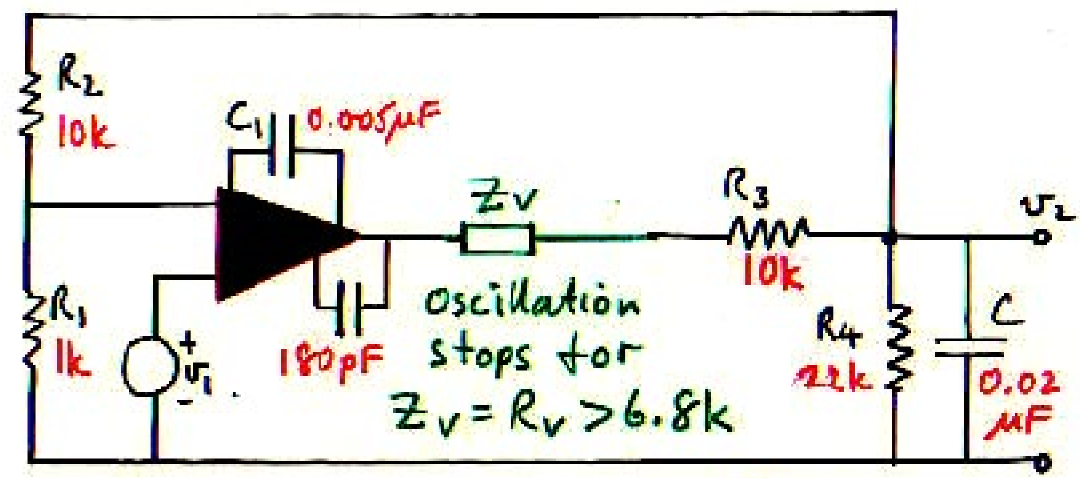

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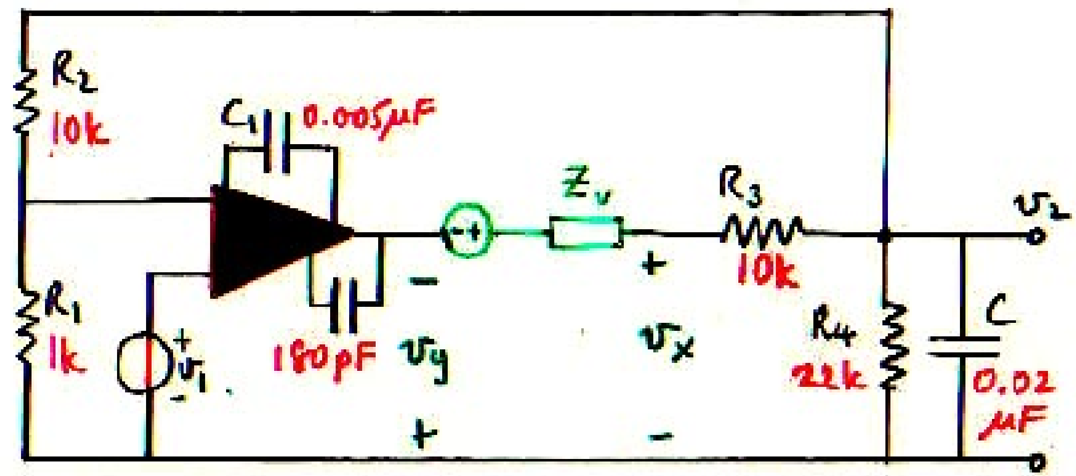

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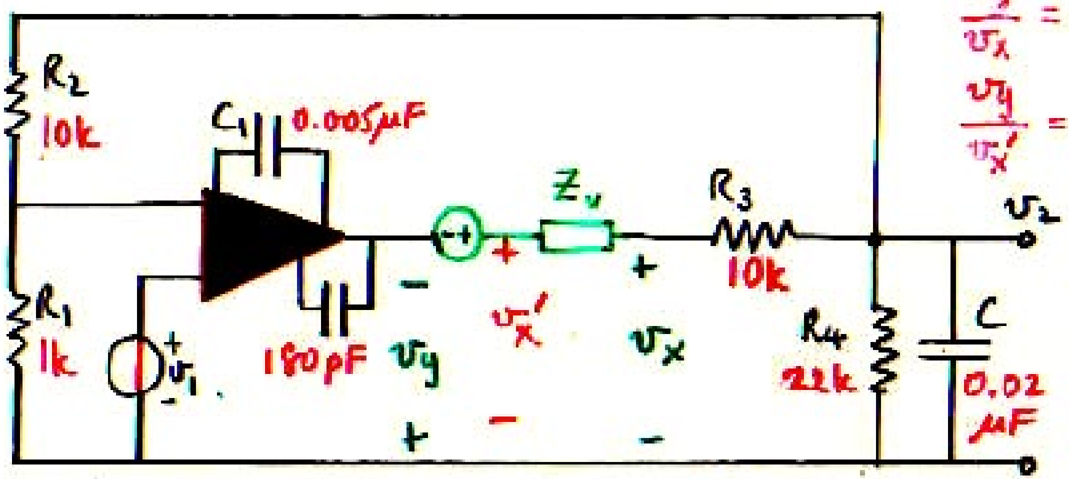
Measurement of an unstable loop gain.

Suppose the following amplifier has been designed:

$\frac{v_y}{v_x} = T\text{(old)(unstable)}$

$\frac{v_y}{v_x'} = T\text{(new)(stable)}$



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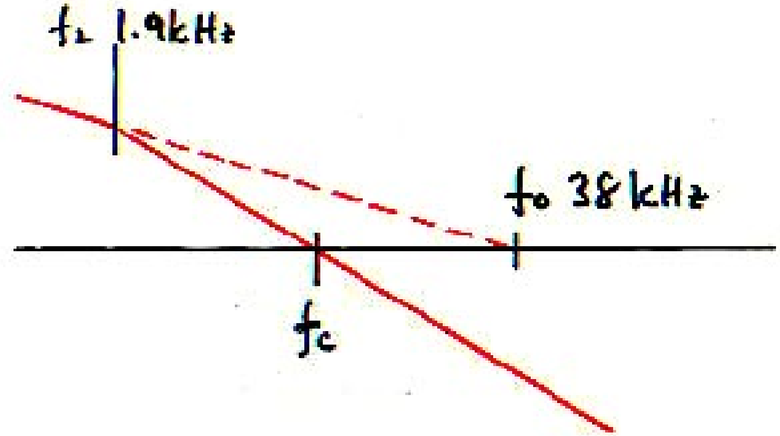

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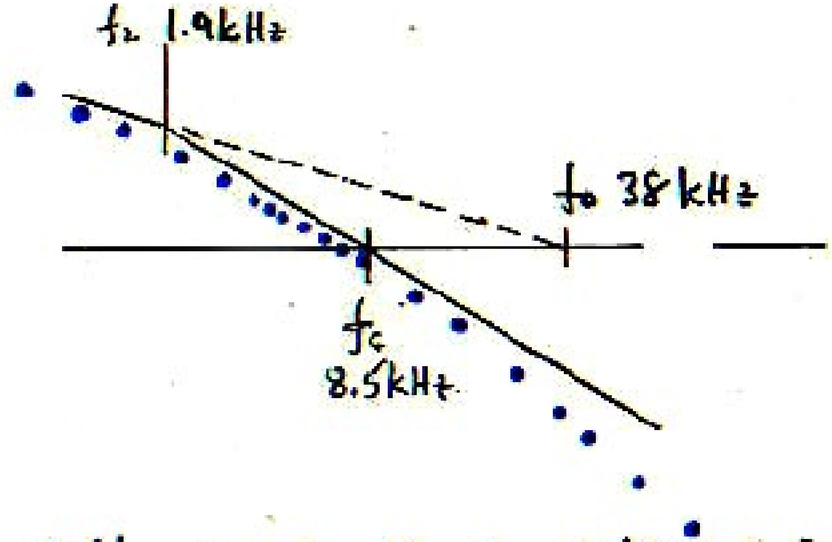
Since f_c is far from f_2, the actual crossover frequency is essentially f_c, so ϕ_M can be checked directly from:

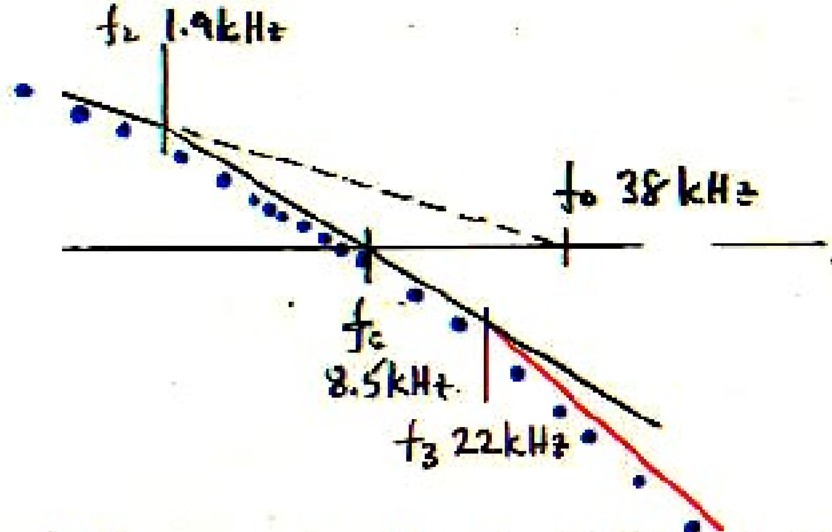
$$\phi_M = 180 + \angle T\big|_{f=f_c} =$$



The Q of the quadratic in $T/(1+T)$ is

$$Q = \sqrt{\frac{\omega_0}{\omega_2}} = \sqrt{\frac{38}{1.9}} = 4.5 \Rightarrow 13\,dB$$

Hence $\phi_M = 14°$



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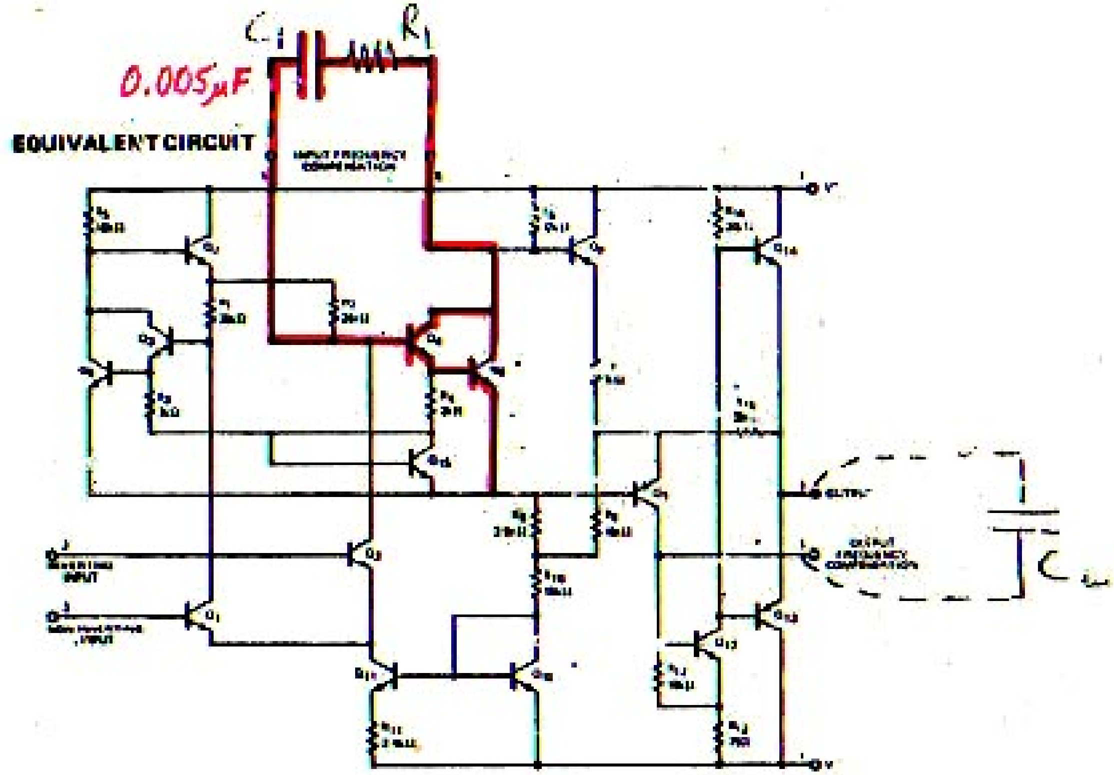
There is actually a third pole at $f_3 = 22kHz$, giving an additional phase lag at the crossover frequency of $\tan^{-1}\frac{8.5}{22} = 21°$.

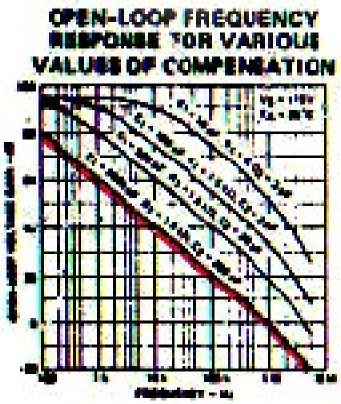
Hence, the actual phase margin is

$$\phi_M = 14° - 21° = -7°$$

and the circuit is unstable.

In the normal design–analyze–measure sequence, the loop gain T is first predicted analytically.





With a 0.005uF compensating capacitor C_1, the gain-bandwidth product is 1 MHz

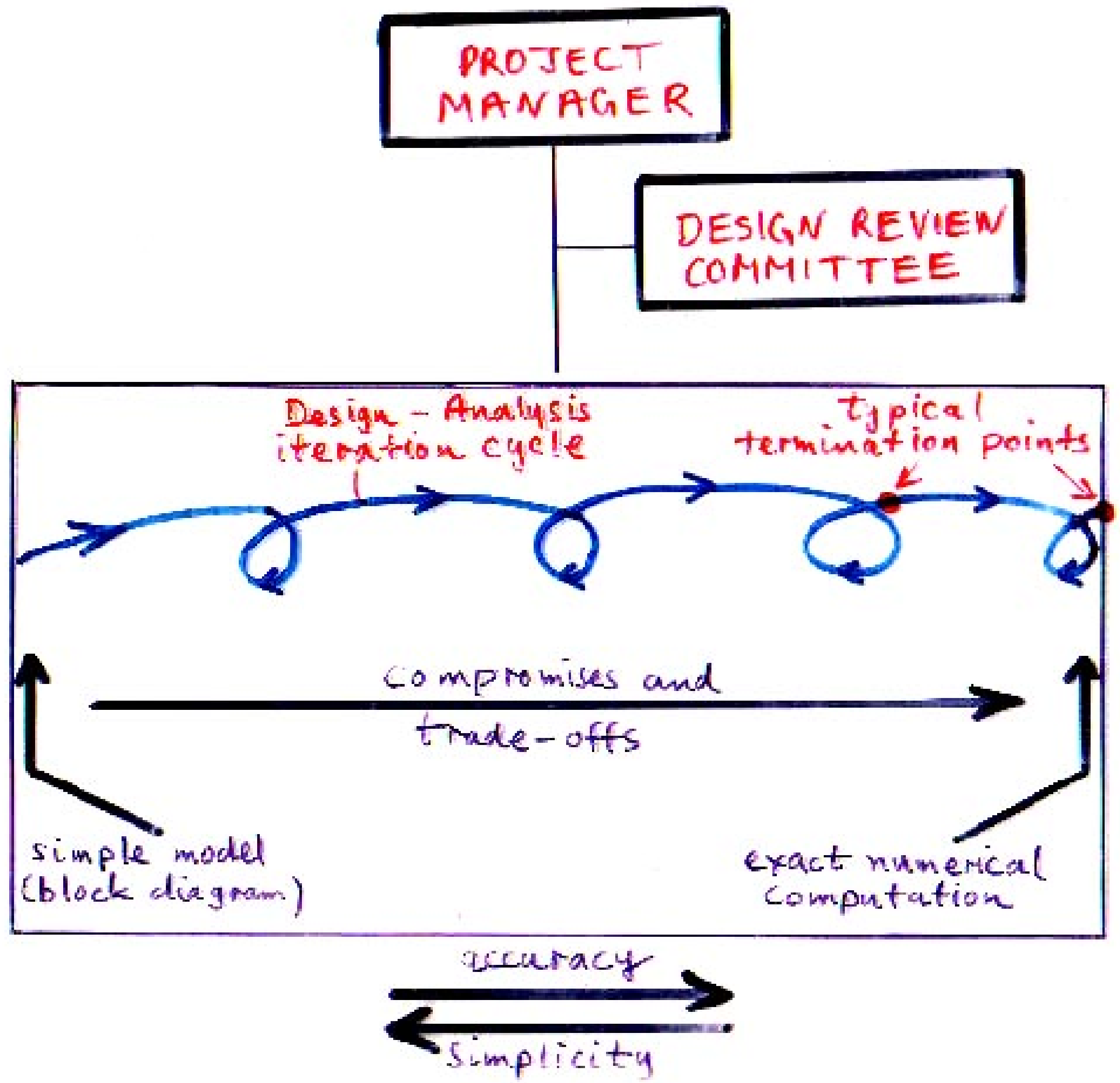
The third pole at f_3 occurs because the 1.5k resistance in series with the 709 compensating capacitor $C_1 = 0.005\mu F$ was omitted; this should provide a zero at $159/0.005 \times 1.5 = 22kHz$ that is to compensate an internal pole at 22kHz. This is the observed pole that was omitted from the prediction, and caused the instability.

Generalization: Measurement of Loop Gain in an Unstable System

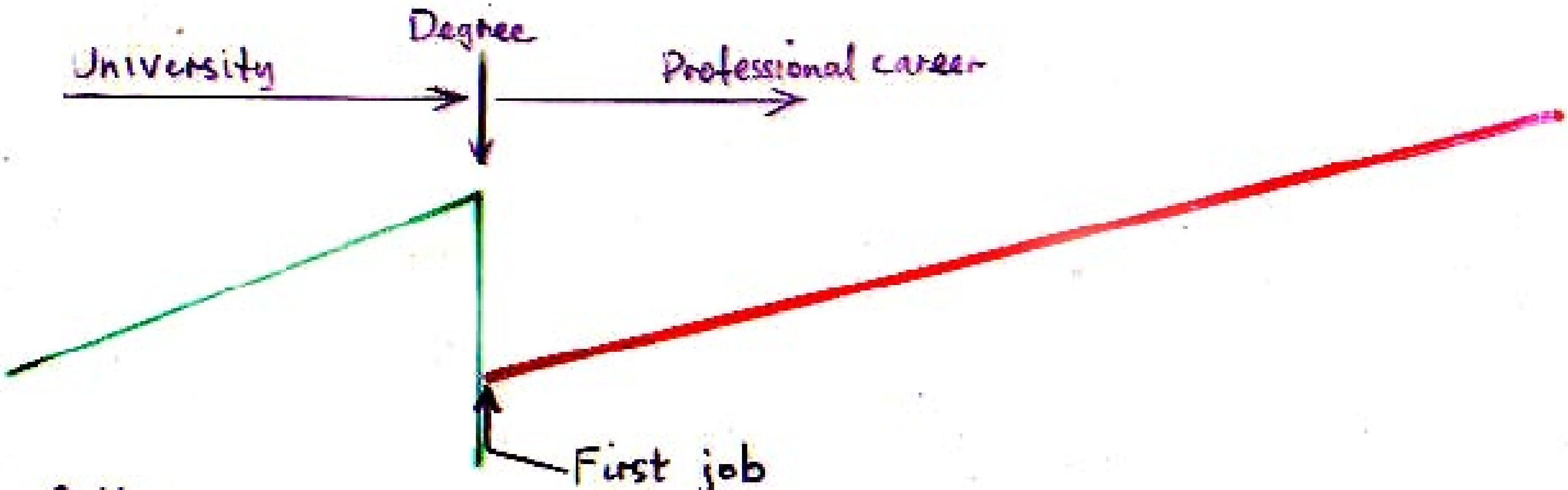
The system can be made stable without affecting the measurement of the original unstable loop gain:

At the point where signal injection is to be done, insert a sufficient impedance to stop the oscillation. Then, inject the test signal and measure the original unstable loop gain on either side of the combination test signal source and stabilizing impedance.

This result also implies that the source impedance of the test signal is irrelevant in the measurement of any loop gain, stable or not.



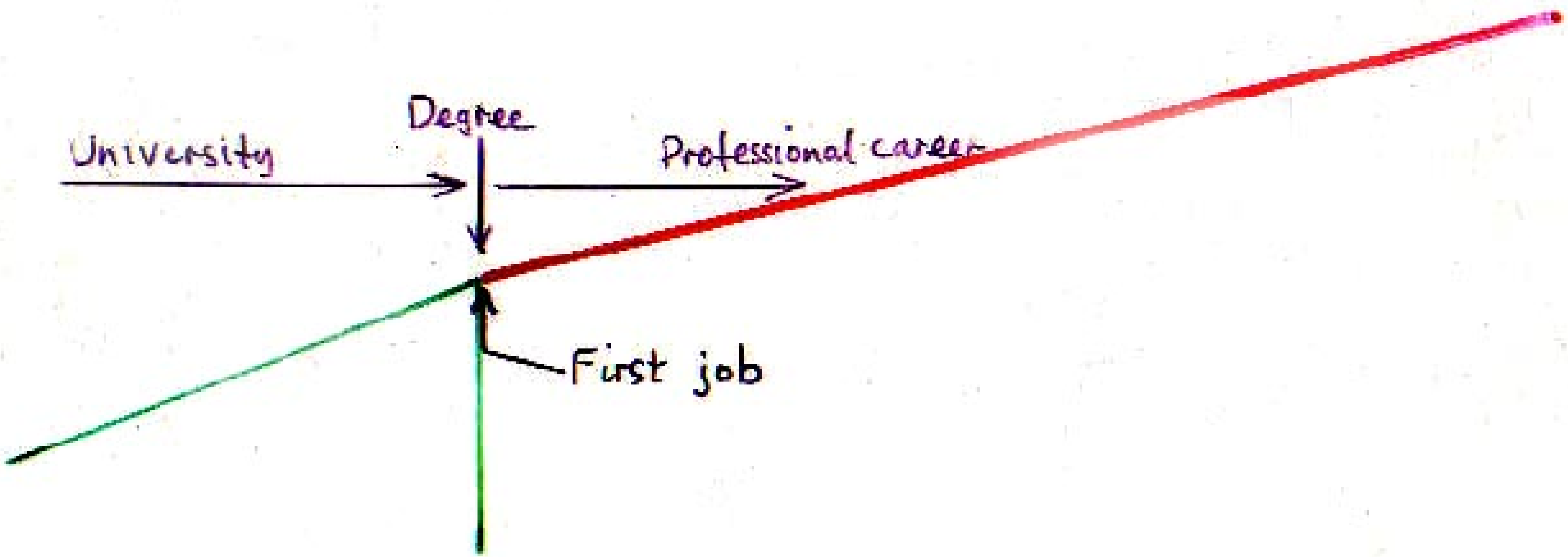
PROJECT MANAGER
DESIGN REVIEW COMMITTEE
Design - Analysis iteration cycle
typical termination points
compromises and trade-offs
simple model (block diagram)
exact numerical computation
accuracy
simplicity



Problem:

New graduate engineers are unable to translate the principles and methods they have learned to the real world.

What can be done?



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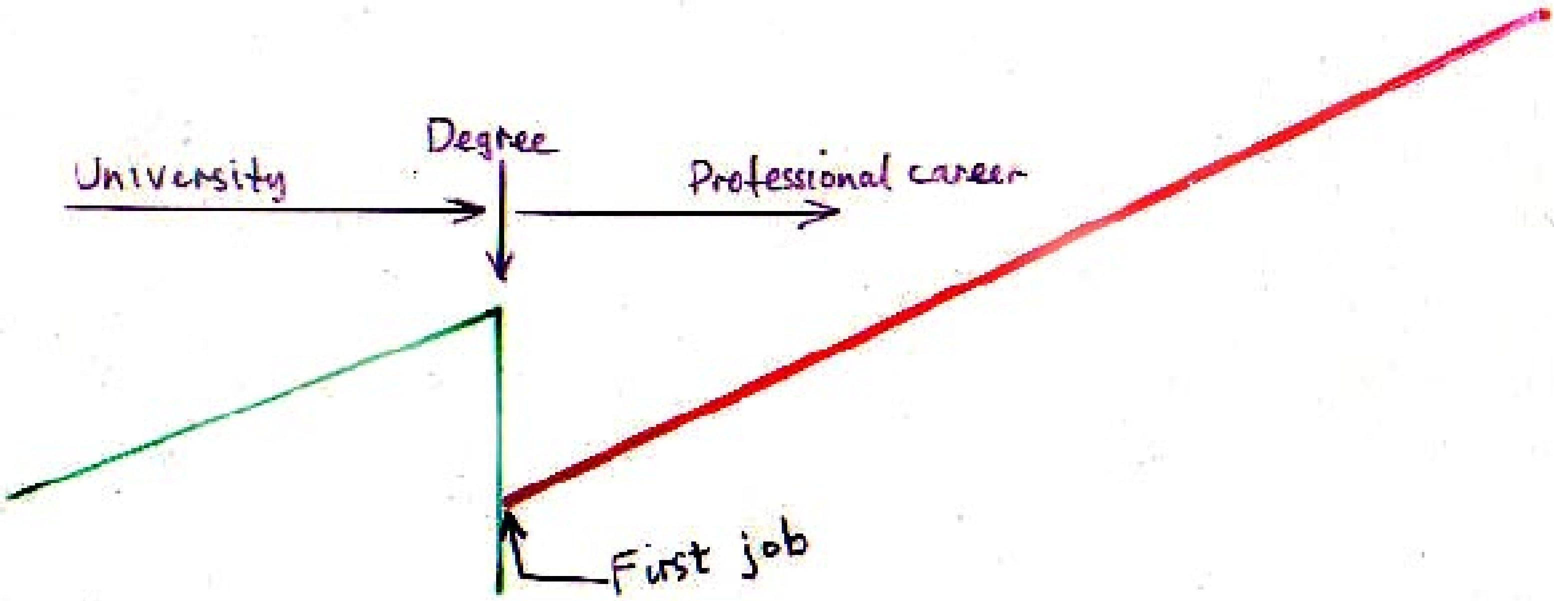

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