Noise Measurement for Obtaining Optimum Point of Detection System by Using Field Effect Transistor (FET)

أفضل نقطة حساب للضوضاء في أنظمة الكشف باستخدام ترانسستورذات المجال المؤثر (FET)

L.Haider Khder Lateef A.L. Mukhalad Kadom Marza A.L. Mohanned Hassan Ali
Department Engineering of
Technical Electrical Power
Technical College/ Musayab

Abstract:

The designed circuit in this research is measured several types of noise and it's analysis, reduction and amplification of received signal value by using the detection system type Field Effect Transistor (FET Tr) the aim of using this type of amplifier in designed system because of it's efficient matching between input and output impedance, this will increase performance in detection of signal and noise. Also, all equations that help in calculation of noise voltage and noise current are derived and effect of bias resistance and capacitance of detector also was studied. Research study shows that the preamplifier noise is primarily influence by the first stage noise provided that the gain of that stage is large (Kt=8.87), total noise voltage to detection system (En T=3.314 nV), total noise current (InT=5.41 fA), noise figure (NF=0.0093 dB) at optimum source resistance and the detector resistance (2.5 MΩ) photoconductive type.

الخلاصـــــــة:

يتناول هذا البحث تصميم دائرة قياس عدة أنواع للضوضاء وتحليلها،كيفيه تقليلها وتكبيرقيمة الاشاره المستلمة من قبل منظومة الكشف وتكبيرها بمكبرات نوع ترانسستور ذات المجال المؤثر (FET Tr) والسبب في استخدام هذا النوع من المكبرات في المنظومة المصممة لكفائته في الموائمة بين ممانعة الادخال والاخراج ممايؤدي الى زيادة الاداء في كشف الاشارة والضوضاء.كذلك تم اشتقاق المعادلات الخاصة لحساب قيم فولتية الضوضاء (En) وتيار الضوضاء (In) ودراسة تأثير مقاومة الانحياز والسعة على ضوضاء الإدخال للمنظومة, تحتوي الدائره المصممة على كاشف نوع (photoconductive). وأظهرت نتائج الدراسة أن الضوضاء المكبر الأولي (preamplifier) تتأثر بشكل كبير بضوضاء أول مرحلة تكبير وكانت ذات عامل ربح عالي(Kt=8.87) وفولتية الضوضاء الكلية لمنظومة الاستلام هي(EnT=3.314 nV) وتيار الضوضاء الكلية (InT=5.41 fA), وكان رقم الضوضاء (noise figure) هو (NF=0.0093 dB) عند قيمة أفضل مقاومة مصدر, و قيمة مقاومة الكاشف (photoconductive detector resistance) بحدود (2.5 MΩ).

I. Introduction

The noise is originating from source fluctuation or of background radiation, photon noise associated with random arrival of photons from steady source; from the detector it self, or from the amplifying system. Back ground radiation makes important contribution to noise in IR because spectrometer and surrounding radiate at (10mm) (background ignored <1μm). Detectors noise comes from the dark current a single in the absence of incident radiation which thermal in origin [1].

However, we are interested only in the random electrical fluctuations generated in circuit elements and note in externally generated effects such as static, power supply and ignition noise [2].

The primary requirement is for anise figure that is so low that the noise from the detector is the limiting source of noise in the system. Unfortunately no signal preamplifier can provide optimum performance with all of the available detectors [3].

In the transistor noise model used by Vander Ziel shot [4] and (1/f) noise voltage generators are in series with the emitter; a thermal noise- voltage generator is in series with the base, shot and (1/f) noise current generator are in parallel with the collector. A simplified noise model for use at frequencies above the (1/f) region had been carried out. [5].

II. Theory

The detector total noise (Vn) is given by:-

$$Vn=\sqrt{\sum_{1}^{n} Vni^{2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

Where (Vni) represents the particular noise source voltage (current) involved in the radiation detection process.

The typical frequency dependence of the detector noise current (voltage) is shown in fig (1). [6].There are several types of noise:-

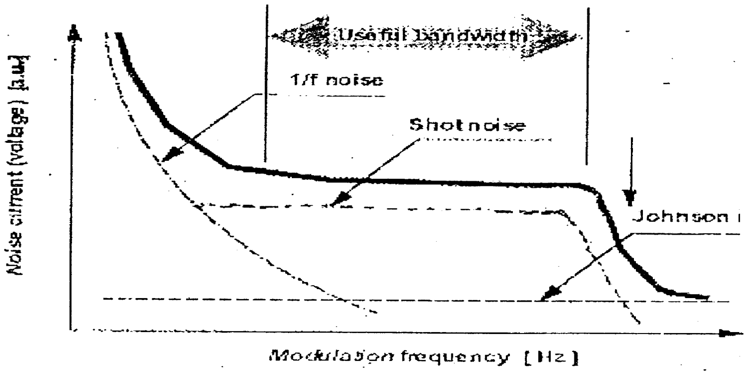

Fig. (1) Noise Sources

II.I. Low Frequency or (1/f) Noise

At low frequency there are several types of noise for which the power spectrum varies inversely with frequency. Since this (1/f) noise is greater than, or in excess of shot noise, it's sometimes called excess noise. It is called modulation noise in semiconductors, such as transistors and photo detector, contact noise in carbon resistors and their electrical contacts; and flicker noise in vacuum- tube cathode. In most devices the (1/f) noise becomes negligible with respect to other types of noise at frequencies above a few hundred H Z [7, 8].

II.II. Excess Noise

Many resistors also exhibit excess noise when direct current is present. This noise contribution is greatest in composition carbon resistors and is usually not important in wire wound resistors. Excess noise is so named because it is present in addition to the fundamental thermal noise of the resistor [8].

II.III. Thermal Noise [3, 9]

In 1928 Johnson showed experimentally that a resistor acts as a generator of noise having a mean-square – voltage.

$$Et^{2}=4K.T.R.\Delta f \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

where

K= Boltzman constant $=1.38*10^{-23}$ w.sec/k

T= temperature of the conduction in (k)

R= its resistance in (Ω).

Δf= noise band with of the measuring system in HZ.

A more complete expression for thermal noise is:-

Et^2=4K.T.R.P (f).Δf
where
p (f) is referred to as the plank factor: [7]
P (f) = (h.f/K.T). $(e^{h.f/K.T}-1)^{-1}$
and h= $6.62*10^{-34}$ J.sec , in plank's constant.
When designing a system, frequency limiting can be incorporated in of the later stages. For a laboratory application, frequency limiting can be obtained from wave analyzers, tuned voltmeters and filters. It is usually undesirable to do the frequency limiting with the sensor or the i/p – coupling network.This tends to decrease signal and sensor noise, but it does not attenuate the amplified noise that is generated following the coupling network [9].

II.IV. Thermal Noise Equivalent Circuit

In order to perform a noise analysis of an electronic system every element that generates thermal noise is represented by an equivalent cct composed of a noise voltage generator in series with a noiseless resistance (R) connected between terminals (a) and (b). As shown in fig (2)[7].

$I_t = (4KTD_f / R)^{1/2}$ …………………………………….. (3)

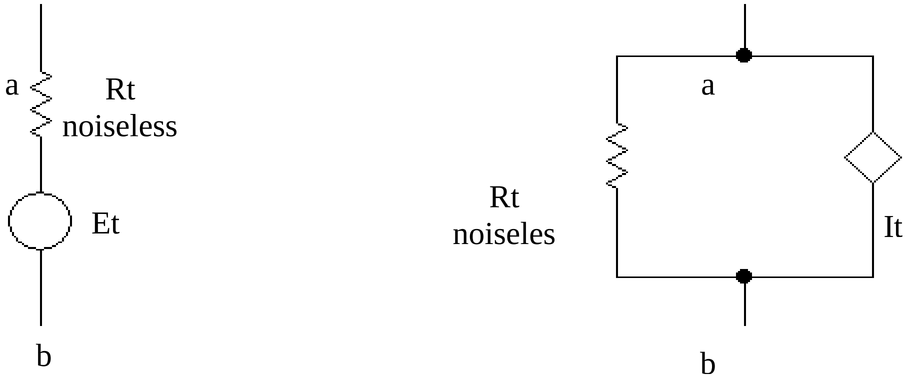

Fig. (2) Equivalent circuits for Thermal Noise

II.V. Shot Noise

In tubes, transistors and diodes there is a noise mechanism called shot noise. Considering the case of vacuum tube diode with high plate voltage so that all the electronics emitted from cathode are collected. The r.m.s value of the shot noise current is observed to be given by [7].

$I_{sh} = \sqrt{2q.I_{dc}}\Delta_f$ …………………………………...…… (4)

where
q= electronic charge ($1.6*10^{-19}c$)
I_{dc} =direct current in A.
Δ_f =noise band width in HZ.

III. Amplifier Noise

Since every electrical component is potential source of noise, a network such as an amplifier that contains many components could be difficult to analyze from a noise stand point.

III.I. Noise Voltage and Current Model

There are universal noise models for any two-part network. This noise model, shown in fig(3),is used to represent an amplifier; it can also apply to passive ccts, tubes, transistors, tunnel diodes, integrated circuit (Ic) amplifiers, and so on. Figure also includes the signal source Vs and noisy source

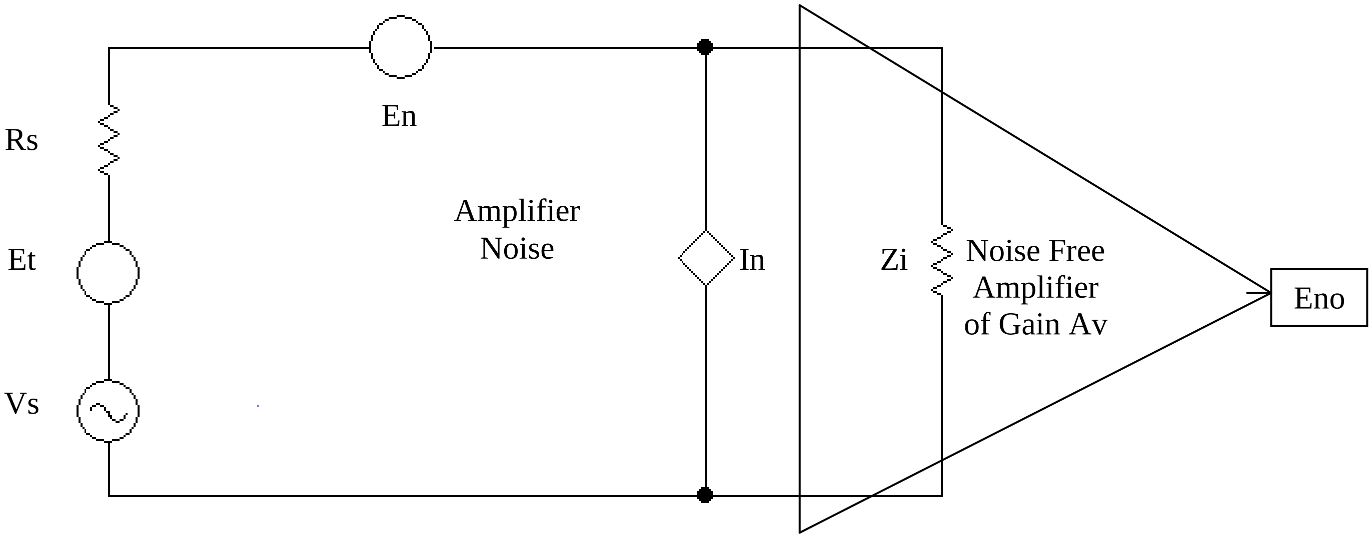

Fig. (3) Amplifier Noise Model and Signal Noise Source

III.II. Equivalent Input Noise [7]

Although the number of the noise sources have been reduced to three sources in the system shown in fig(3) by using the(En-In) model for the electronic circuitry, additionally simplification can be used (equivalent input noise) Eni. This parameter refers all noise sources to the signal source location. The total noise in the output part is,

$Eno^2 = Av^2.Eni^2$ ……………………………………... (5)

Therefore

$Eno^2 = Av^2.[(En^2+Et^2).Zi^2/(Rs+Zi)^2+In^2.Zi^2.Rs^2/(Rs+Zi)^2]$……….(6)

The transfer function from i/p source to o/p is called system gain Kt.by definition,

$Kt=Vo/Vi$ ………………………..…………….. (7)

Note that (Kt) is different from the voltage gain (Av); it is dependent on both amplifier i/p impedance and generator impedance and varies with frequency.

The r.m.s o/p signal can be expressed by:

$Vo=Av.Vs.Zi/Rs+Zi$ …………………………….………. (8)

Sub. Equ(8) into equ(7) gives an expression for the system gain Kt in terms of network parameters;

$Kt=Av.Zi/Rs+Zi$ ……………………………………….. (9)

The total o/p noise given in equ(6) divided by the system gain given in equ(9) yield an expression for equivalent i/p noise;

$Eno^2/Kt^2 = Eni^2$ ....…………………….. ……………. (10)

The expression for equivalent i/p noise is;

$Eni^2=Et^2+En^2+In2.Rs^2$ . ... ……………………...………… (11)

This equation is important for the analysis of many noise problems.

Amplifier i/p resistance and capacitance are not present in the equivalent i/p noise expression. A noise analysis is some what simplified when the loading caused by the amplifier i/p impedance is neglected.

III.III. Noise Figure:

Noise factor, F, also called figure; is a figure-of-merit for a device or a cct with respect to noise. [11] This definition of noise factor in equ. form is;

F=(i/p signal-to-noies)/(o/p signal-to-noise)= (Si/Ni)/(So/No) ……….(12)

The logarithmic expression for noise figure Nf is

Nf=10Log F ………………………….……………….. (13)

The noise figure Nf can be defined in terms of En and In.

Thus

Nf=10 Log (Eni^2/Et^2) =10 log ($Et^2+En^2+In^2.Rs^2/ Et^2$) …………. (14)

III.IV. Optimum Source Resistance

The point at which total equivalent i/p noise approaches closeset to the thermal noise. At this point, the amplifier adds minimum noise to the thermal noise of the source; the noise figure reaches a minimum value.

This optimum source resistance is called (Ro/p) or (Ro) and may be obtained from [12].

Ro=En/In / En=In .Rs …………...……………………….. (15)

The value of noise factor at this point can be called Fo/p.

Rearrangement of equ.(14) can yield,

Fo/p=1+En.In/2K.T.Δ_f ……………………...……………..... (16)

Optimum source resistance, Ro, is not the resistance for maximum power transfer. There is no direct relation between Ro and the amplifier i/p impedance Zi. Ro determined by the amplifier noise mechanisms and has bearing on the maximum signal to noise ratio.

III.V. Noise in Cascaded Network

It can be considered now the problem of locating the important noise source within a system. By deriving a usable expression for the noise factor of cascaded network in terms of the characteristic of each network.

The system to be analyzed is shown in fig (4) [12].

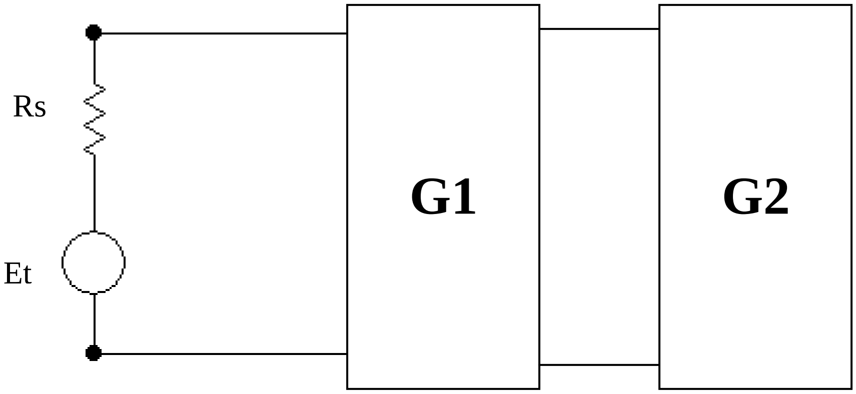

Fig. (4) Cascaded Network

It consist of a signal source with internal thermal noise and two cascaded net works equ.(12) gives noise factor as the S/N.

The available thermal noise power is ($Ni=Et^2/4Rs$), therefore an alternate expression for (F) is;

F=No/Ga.K.T. Δ_f …………………..…….……………… (17)

Where no available noise power at the load terminals.equ.(2-17) is not useful design equation in it's present form because both (No and Ga) are unknown parameters. the available noise power at the i/p to network (Ni_2) is;

$Ni_2=No_1=F_1.G_!.K.T.\ \Delta_f$ .... ……………..………………….. (18)

$F_2=No_2/G_2.K.T.\Delta_f$ .... (19)

The noise originating in the second stage is ($No_2-G_2.K.T.\Delta_f$) or from equ (2-19) it is;

$F_2.G_2.K.T.\ \Delta_f - G_2.K.T.\ \Delta_f = (F_2-1).G_2.K.T.\ \Delta_f$ …... …………. (20)

The total o/p noise (NoT) is given by the sum of terms from equ (18) and equ (20);

$NoT=G_2.\ (F_1.G_1.K.T.\ \Delta_f) + (F_2-1).G_2.K.T.\ \Delta_f$ …………… (21)

The noise factor of the cascaded pair is;

$F_{12}=NoT/G_1.G_2.K.T.\ \Delta_f$ ………………………………..….. (22)

By sub. Of equ (21) in to equ (22):

$F_{12}=F_1+F_2-1/G_1$

If the analysis is extended to three-stage; we obtained the classic relation developed by Friis [13].

$F_{123}=F_1+F_2-1/G_1+F_3-1/G_1.G_2$ .. ……………. …..…………. (23)

One concludes then that the noise factor of a cascaded network is primarily influenced by first-stage noise; provide that the gain of that stage is large.

IV. Procedure and Tools

The equipment used in this test is as following:

1. Precision current source (0-20) A, optronic Laboratories Inc. This current source was used to operate the tungsten ribbon lamp, at (15A) D.C.
2. Spectral radiance standard, model 550, optronic laboratories Inc.as shown in fig (5).
3. Infrared spectro-radiometer, model 746; the grating type used is G-40-150, the monochromater will scan wavelength.

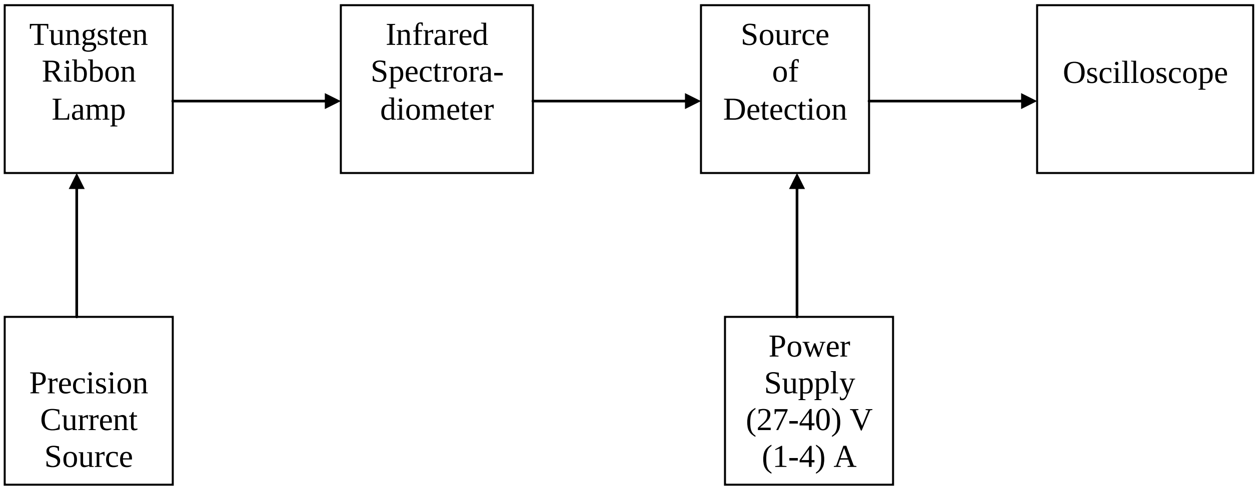

Fig. (5) Spectral Response Test Set [14]

4. The source of detection (type of Si detector mustsubishi).
5. Oscilloscope type synchroscops,model SS-6421,dc-350MHZ,JAPAN.

To measure the current-voltage characteristic (c/cs), the circuit that connected as shown in fig (6).

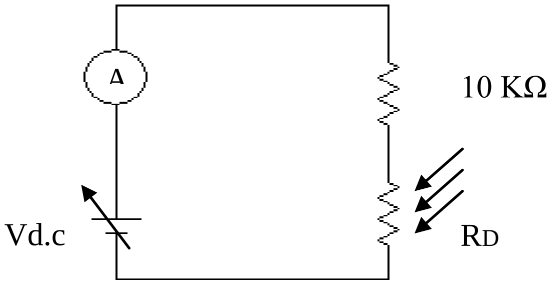

Fig. (6) Test Set For V-I (c/cs)

The d.c power supply Vd.c used in this test is HP6337B, (0-25) V, (0-2) A, and the ammeter (A) type, is Fluke; model 8010 A digital multimeter. To measure the transfer voltage gain (Kt) at various frequencies a function generator (Vs) was inserted in series with source impedance (sensor), and the signal (V_o) was measured. Transfer voltage gain (Kt) is the ratio of V_o to Vs.

The test is set as shown in fig (7). A voltage divider composed of two resistors (each 56 Ω) was connected across i/p terminals of the function generator to avoid the amplifier saturation, operational amplifier type (TL084).

The function generator type is (HP) model 8816 A (50 MHZ).

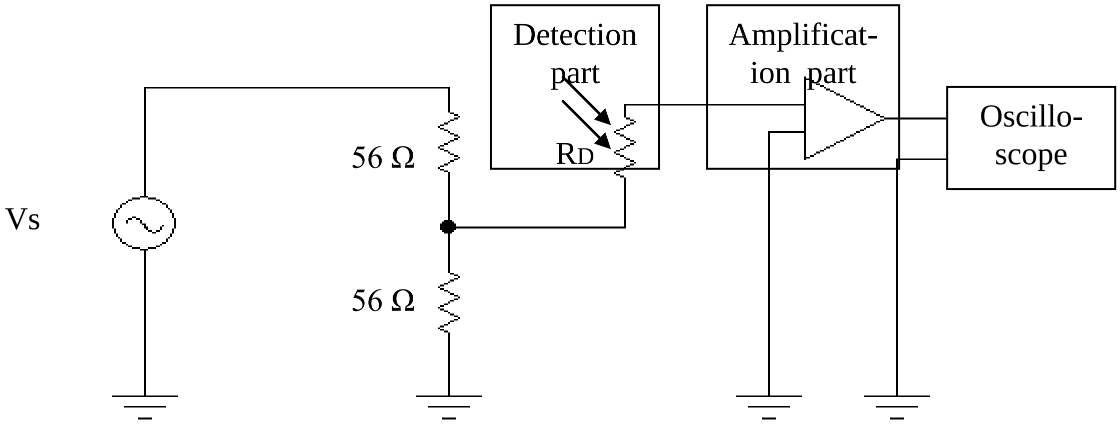

Fig. (7) Amplifier Frequency Response Measurement

V. Results and Discussions

The low noise design concerned with the following problem:

Given a sensor with known signal, noise, impedance and response characteristics (c/cs). Now how to optimize the amplifier design to achieve the lowest value of equivalent i/p noise?

1. Amplification portion of the system must be matched to the sensor. This matching is the essence of low-noise design.
2. Sensor impedance and the first stage (Q), of the amplifier determine the ultimate limit on equivalent input noise.
3. Source impedance $Z_{s\ (f)}$ and noise generator $E_{n\ (f)}$ and $I_{n\ (F)}$ representing Q1 are each a different function of frequency.
4. Initial steps in the design procedure are the selection of the type of input device, such as bipolar transistor, FET or Ic, and the associated operating point to obtain the desire noise c/cs. After selecting i/p stage the circuit (cct) is design.
5. Noise in FFT device was introduced in the theory. Because of the high impedance of the sensor used in our application, the FFT is an attractive i/p device[8]. In the common source (cs) configuration infinite i/p impedance. The circuit (cct) diagram of this connection is shown in fig (8-a); the gate to channel diode of this n-channel FET is reversed biased.
6. The biasing network contains a resistance (RG1) connected between the junction of (RA1), and (RB1), and the FET gate. Fig (8-b) shows the small signal (ac) and noise equivalent cct for this connection. The voltage gain provide by the (cs) is.

$Kt=g_m.RL/1+g_m.Z_{s1}$ ……..…………………………………... (24)

Where $RL=RD_1 /\!/ r_o$

$Z_{s1}=R_{s1} /\!/ -j.X_{s1}$

The equivalent input noise is equal [11];

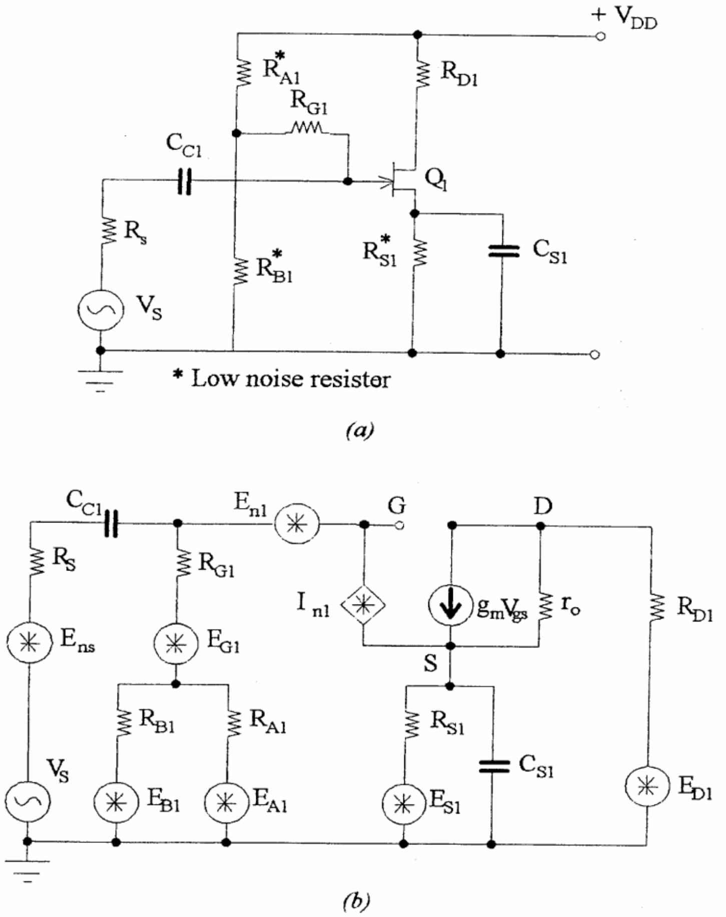

Fig. (8): Parallel CS Amplifier: (b): Noise Equivalent

$Eni^2=Ens^2+En^2(RG+RS/RG)^2+In^2(Rsj.Xc1)^2+[E_{A1}^2(R_{B1}/R_{A1})^2+E_{B1}^2(R_{A1}/R_{B1})^2+E_{G1}^2].R_S^2/R_{G1}^2+(Es1/w.Rs1.Cs1)^2+E_{D1}^2/K_{t1}^2$ ..……………………….... (25)

The source by pass capacitor Cs1 determines the break frequency f. the angular frequency at which the voltage gain is (3dB) below the mid frequency value is;

$WL=1/C_{S1}.R_{S1}.[ro+RD1/(gm.ro+1).R_{S1}+ro+R_{D1}]$ ……….……....(26)

7.The frequency response for detection system preamplifier as shown in fig (9).the amplifier has a peak gain response at (72) dB; the gain response has a sharp low cut-off frequency at about (1040) HZ.this will attenuate the (1/f) noise originates in the sensor and the i/p stage of the preamplifier.

The result of detector (V-I) c/cs is shown in fig (10). The detector has linear c/cs over voltage range (2-24) V under dark condition. The curve indicates that the sensor is photo conductive detector having a resistance about (2.4 MΩ). The measured capacitance is about (0.165 μf) which represent the sum of series and shunt wiring capacitance.

The spectral response of detection system in the amplifier as shown in fig (11); the curve has a peak value at (3.9 μm). For common stage shown in fig (8).

The dc-load-line equation

$V_{DD}=V_{DS}+iD\,(R_{D1}+R_{S1})$ ………………………………….. (27)

and the gate voltage is:-

$V_{GS}=(R_{B1}/R_{A1}+R_{B1}).V_{DD}+i\,D.R_{S1}$ ……...……………………… (28)

To design the amplifier for a (Q-point) at (V_{DS}=5 V) and (I_{DQ}=1mA); sub these values (V_{DD}=15 V) in to equ. (27):-

$R_{D1}+R_{S1}=V_{DD}+V_{DSQ}/I_{DQ}=10\ K\Omega$

Optimum amplification value for resistance R_{S1}& R_{D1} is (R_{S1}=4.9 KΩ) and R_{D1}=4.9 KΩ); then (I_D=.97 mA) the Q-point occurs at a gate-to-source voltage:-

$V_{GSQ}=-0.25\ V$

Then; using equ. (28) getting:-

$(R_{B1}/R_{A1}+R_{B1}).V_{DD}=5V$

For (RA1=1 MΩ); then (R_{B1}= 490 KΩ)

For cct diagram shown in fig (8); the i/p noise E_{ni} was given in equ.(25); to get the preamplifier i/p noise calculation.

This equ.can be separated in to two parts, E_{nT} and I_{nT}.

For $R_S \longrightarrow 0$

$E_{nT}^2=E_{n1}^2+I_{n1}^2.X_{c1}^2+(E_{s1}/w.R_{s1}.C_{s1})^2+E_{D1}^2/Kt1^2$ …..................... (29)

And for $R_S \longrightarrow (\infty)$

$I_{nT}^2=I_{n1}^2+[E_{A1}^2*(R_{B1}/R_{A1})^2+E_{B1}^2*(R_{A1}/R_{B1})^2+E_{G1}^2]*1/R_{G1}^2$............ (30)

For $R_{G1}=10^9\ \Omega$; Cs1=22 μf ; Cc1=33 nf ; ro=20 KΩ typical value

From equ.(24), then Kt1=8.7

By using equ.(2):-$4K.T=1.6*10^{-20}$ (at room temperature 290 K)

The thermal noise levels in $R_{A1},R_{B1},R_{G1},R_{D1},R_{S1}$ are:-

$E_{A1}=(1.6*10^{-14})^{1/2}$ = 126 nV

$E_{B1}=(7.52*10^{-15})^{1/2}$ = 87 nV

$E_{G1}=(1.6*10^{-11})^{1/2}$ = 4 μV

$E_{D1}=(8.16*10^{-17})^{1/2}$ = 9 nV

$E_{S1}=(8.16*10^{-17})^{1/2}$ = 9 nV

the terms in equ.(27) are :-

$E_{n1}=3.16\ nV \longrightarrow Z_{n1}.X_{c1}=0.014\ nV$

$I_{nT}=5.31\ fA$

The optimum source resistance is: - $Ro=E_{nT}/I_{nT}=625\ K\Omega$

Uising equ.(14), the noise figure at R_o is :-
NF=0.0093 dB

The measurement frequency response for the preamplifier having the above component values is shown in fig (12). This measurement was done at i/p r.m.s voltage level of (7 mV).the o/p r.m.s voltage was (72 mV) at (1.2 KHZ).

The static drain current of Q1 (I_{Ds}= 0.98 mA) is at relatively high level. The reason for operating at high level of I_D was given in the theoretical part, to minimize the (E_n) parameter.Unfortunaly; this selection for I_D results in relatively low values for the drain load resistor (R_D).since voltage gain in the connection proportional to (R_D), we are not able to develop high gain in the i/p stage. After selection the i/p stage the cct is design. The biasing is set up, and the coupling network is determined; then the total noise of the entire system is analyzed; including the bias network contributions to ensure the design still meet the noise specifications.

At high values of source resistance (FET) are more desirable because of their very low noise current (In). In some instances they are even preferred when low En is desired. A good (FET) has En slightly larger then that of a bipolar (Tr), and it’s (In) is significantly lower. Another advantage of the (FET) is it’s high i/p resistance and low capacitance; thus it’s particularly useful as a voltage amplifier.

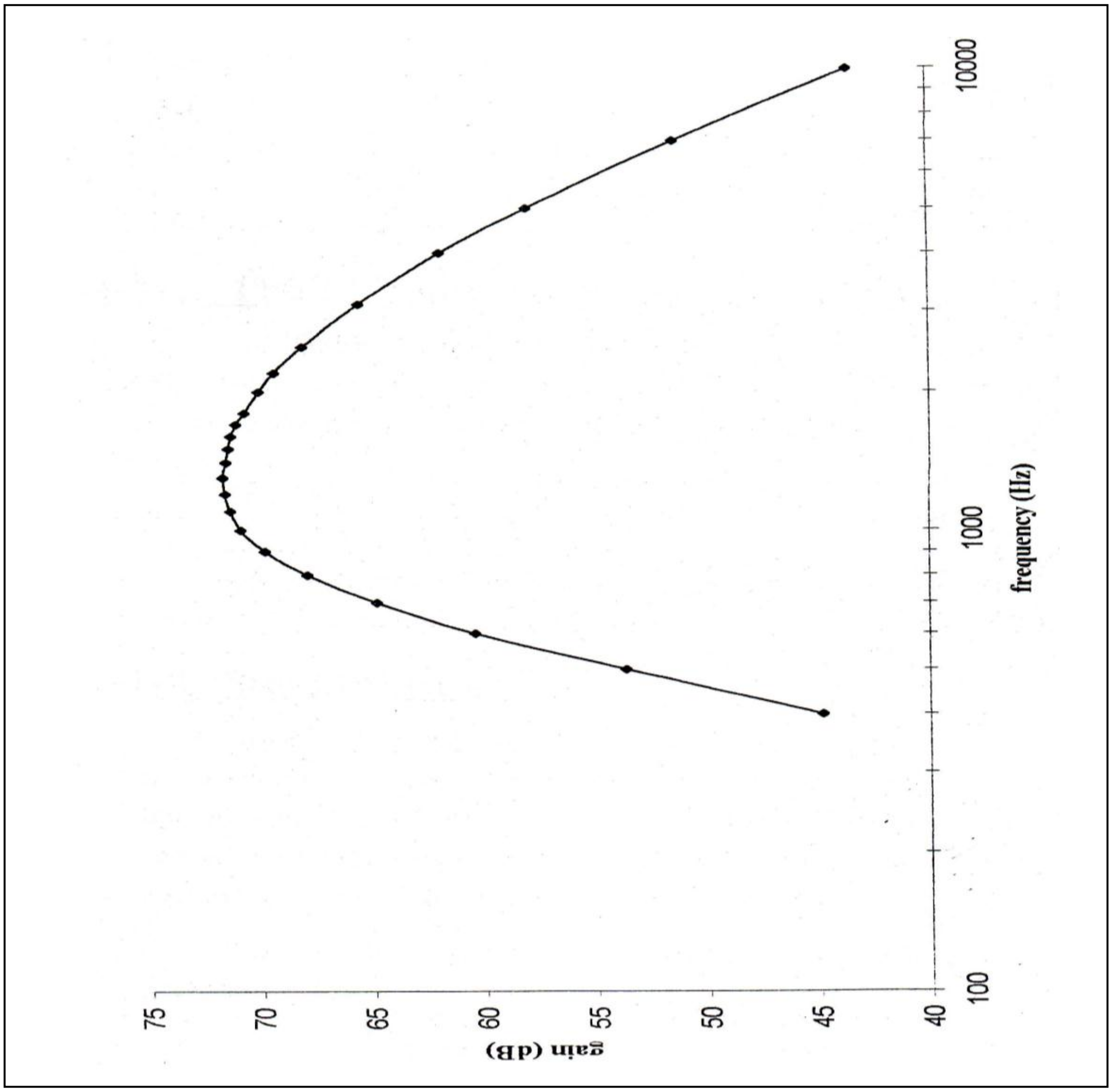

Fig.(9) Frequency Response for Detection System Preamplifier .

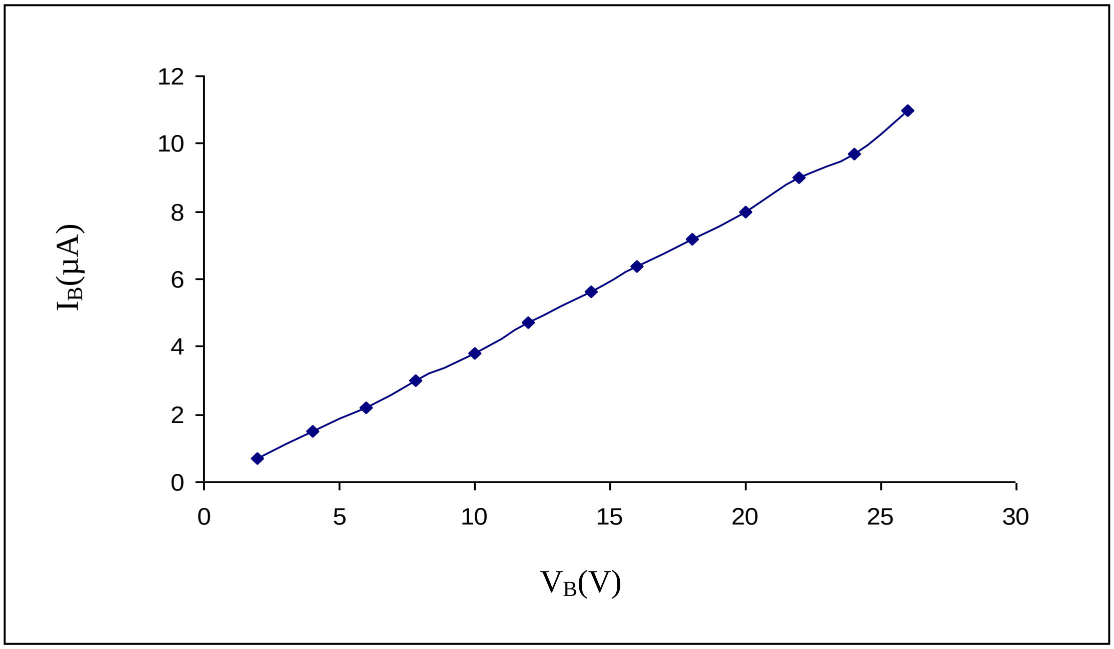

Fig.(10) Current – Voltage Characteristics .

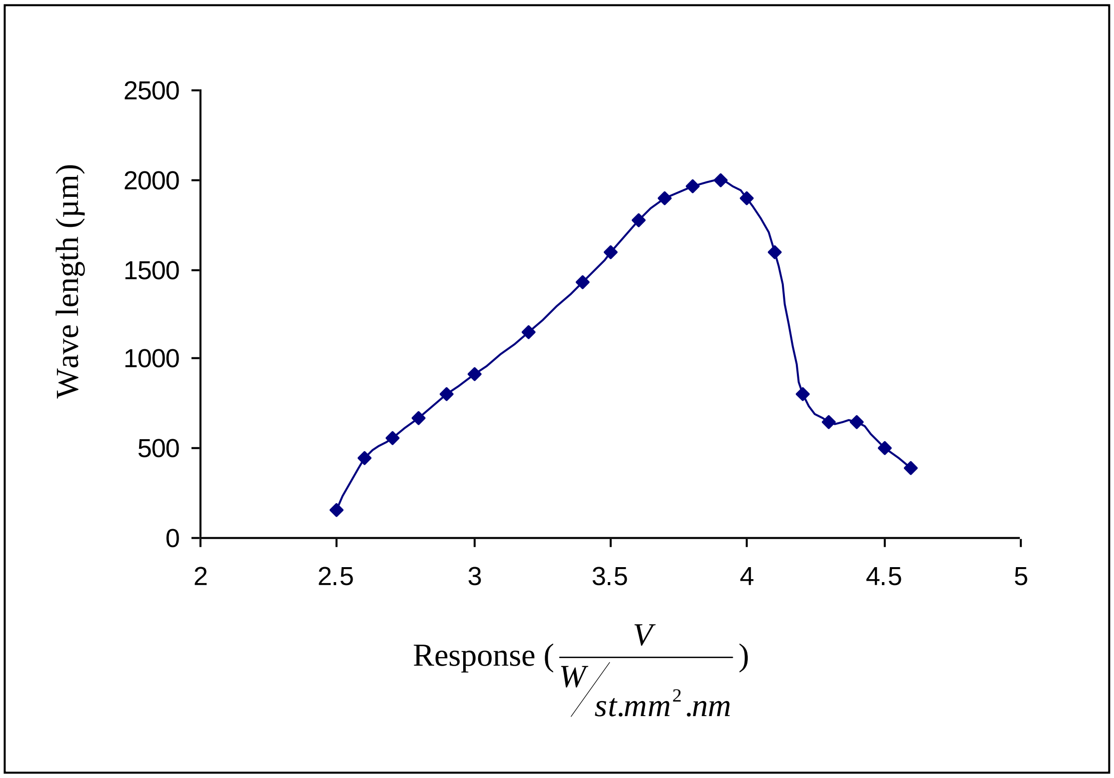

Fig.(11) Spectral Response for Detection System in the Amplifier .

Fig. (6)
Test Set
For V-I
(c/cs)

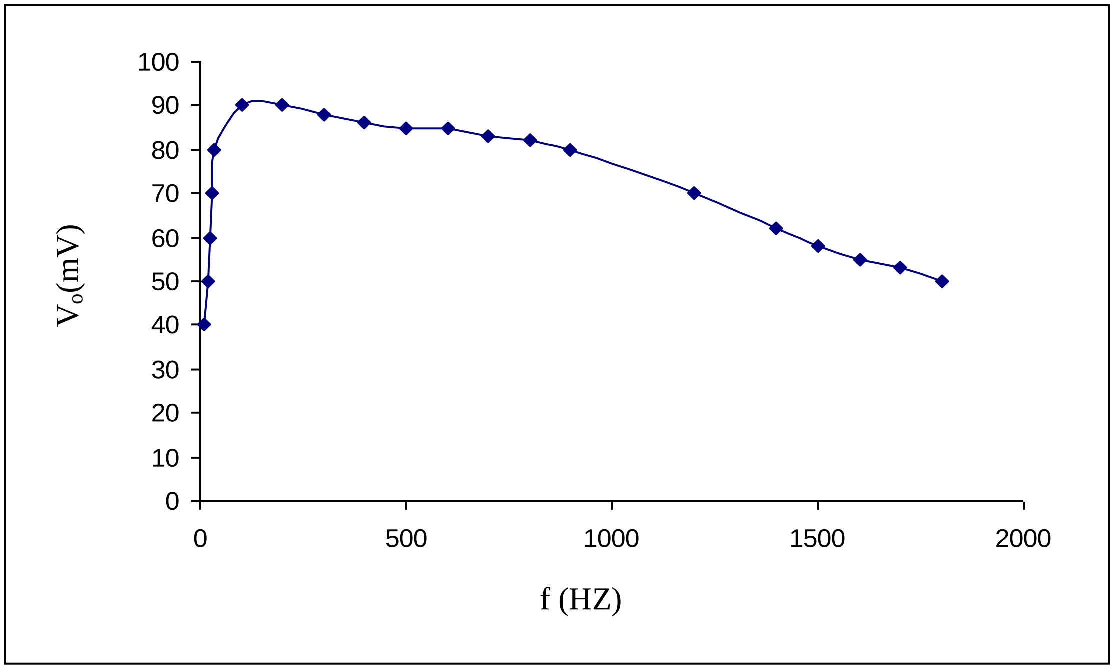

Fig.(12) Frequency response for the Designed Preamplifier .

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