Design of a 4 GHz LNA for a TVRO System

Application Note A002

Introduction

With the advent of low cost GaAs FETs, the consumer home entered a new phase in communications: the era of satellite television reception. A typical Television Receive Only (TVRO) system for this market is shown in Figure 1. The consumer end of this system consists of an antenna to receive the satellite signal, a low noise amplifier or LNA to amplify the signal received by the antenna to a high enough level that it can be processed, a converter to change the frequency of the amplified signal from the satellite broadcast frequency to the frequency band in which the TV receiver operates, and a TV receiver to translate the signal into electrical impulses that will be changed into pictures and sound by the consumer's television set.

This note describes the design of a six stage LNA for such a system. The operating frequency of this LNA is 3.7 – 4.2 GHz, the most common band in the United States.

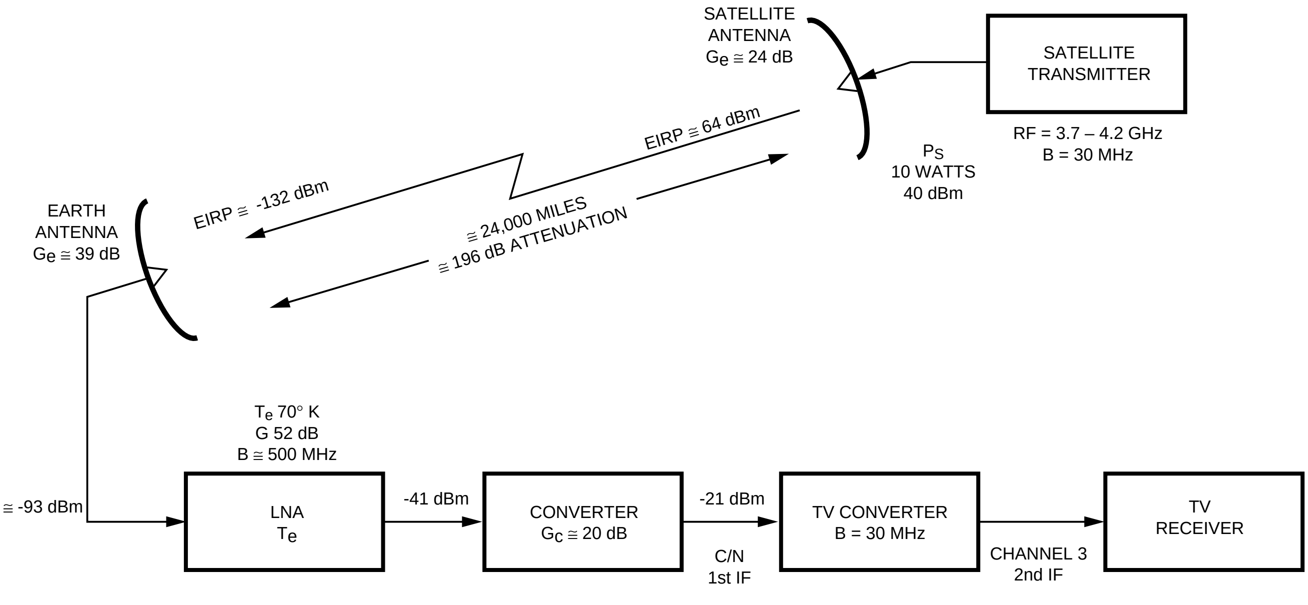


Figure 1. Satellite RF Down-Link Diagram for TVRO System with Typical System Parameters

LNA Specifications

The quality of the TV picture produced by a TVRO system is determined by the ratio of the gain of the earth antenna to the effective input noise temperature of the system (noise temperature of LNA plus noise temperature of antenna). This ratio is called the G/T ratio. It is important to the consumer since it shows that picture quality can be improved in either of two ways. Using a higher gain antenna will raise the system G/T ratio, and hence result in a better picture. Similarly, using an LNA with a lower noise figure will also raise the G/T ratio.

In general, the gain of an antenna is proportional to its size. Unfortunately for the consumer, so is its cost. Since the antenna tends to be the most expensive part of the home TVRO system, the importance of an economical LNA with low noise figure is readily seen.

The G/T ratio can be expressed as a function of the ratio of carrier power (C) to noise power (N) at the receiver, the effective-isotropic-radiated-power of the satellite (EIRP), the down link loss (L_s), the link margin (L_m), and the transmission bandwidth (B). The mathematical relationship is given by:

$$10 \log (G/T) = C/N - EIRP + L_s + L_m + 10 \log(B) - 228.6 \text{ dB}$$

For a typical system,

C/N = 10 dB minimum for good picture quality
satellite transmit power = 10 watts
satellite antenna gain = 24 dB

so

EIRP = satellite transmit power + satellite antenna gain
= 10 dBw + 24 dB
= 34 dBw
distance to satellite = 38,559 km
wavelength (for a 4 GHz system) = 0.075 m

so

L_s = 20 log [(4π) (distance to satellite)/(wavelength)]
= 20 log [(4π) (38,559 km)/(0.075 m)]
= 196.2 dB
L_m = 1 dB
bandwidth = 30 MHz

so

10 log B = 10 log (30 x 10^6 Hz)
= 74.8 dB

therefore

10 log (G/T) = 10 - 34 + 196.2 + 1 + 74.8 - 228.6
= 19.4 dB

(see Appendix 1 for details of the above derivation)

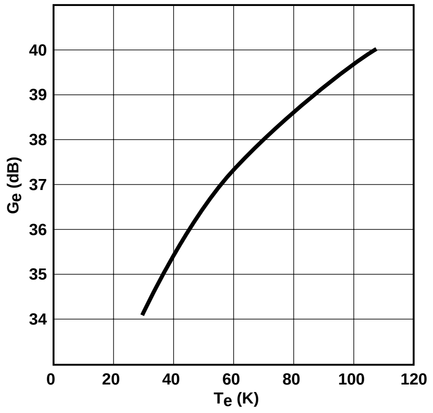


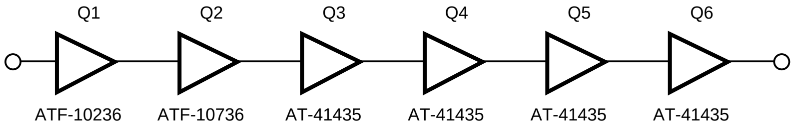
Figure 2. G_e vs. T_e for C/N = 10 dB

Using this relationship, a plot of earth station antenna gain vs. system noise temperature was generated for a C/N ratio of 10 dB (Figure 2). By using the fact that most 4 GHz TVRO antennas have noise temperatures of about 25 K, this graph can be used to find the minimum noise temperature that an LNA must have to provide an acceptable picture when coupled with an earth station antenna of a specified gain. For example, an antenna that has 39 dB of gain would require the LNA with which it is coupled to have a maximum noise temperature of (87-25) K or 62 K.

In addition to having a sufficiently low noise temperature, the LNA must also have enough gain to provide a signal strong enough to drive the converter. From the power levels shown in Figure 1, it can be seen that the LNA should have at least 52 dB of gain across the 3.7 – 4.2 GHz band.

Amplifier Design

The requirement that the LNA have minimal noise temperature dictates the use of GaAs FETs for the first two stages of the design. While GaAs FETs have superior noise performance to silicon bipolar transistors in the 4 GHz frequency range, they are also more expensive. In this design, the first two stages provide about 24 dB of gain. The remainder of the required 52 dB is made up of stages using lower cost silicon bipolars; to insure production margin four stages of silicon are used. The total amplifier chain is given in Figure 3.



	ATF-10236	ATF-10736	AT-41435	AT-41435	AT-41435	AT-41435
GAIN:	10.0 dB	12.0 dB	8.0 dB	9.0 dB	9.0 dB	6.0 dB
NF:	0.8 dB	1.1 dB	3.5 dB	4.0 dB	4.0 dB	4.5 dB

NOTE: Q1 SELECTED FOR F_{min}

DESIGN GOALS: NOISE FIGURE < 1.1 dB
NOISE TEMPERATURE < 85 K
GAIN > 50 dB
OVERALL STABILITY
LOW COST

PERFORMANCE: TYPICAL GAIN 50-54 dB
NOISE TEMPERATURE 60-85 K

Figure 3. 3.7 - 4.2 GHz Low Noise Amplifier

NOTE:
The ATF-10736 has been obsoleted. Please use the ATF-10236 as a replacement.

The device selected for use in stage 1 is the HP ATF-10236. The device can provide the required noise temperatures and gain at 4 GHz, and comes packaged in a cost saving glass sealed package, suitable for use in commercial markets. It has a typical noise figure of 0.8 dB; for stage 2 the less expensive HP ATF-10736 with a typical noise figure of 1.1 dB is used.

The design proceeds form the S-parameters listed on the ATF-10235 data sheet. These S-parameters are repeated in Figures 7 and 8. The noise parameters used for Ql and Q2 are as follows:

Q1: $F_o = 0.8$ dB
$\Gamma_{on} = 0.42 \angle 148°$
$R_n = 3.6$ Ohms

Q2: $F_o = 1.1$ dB
$\Gamma_{on} = 0.43 \angle 152°$
$R_n = 2.1$ Ohms

where G_{on} is the reflection coefficient seen at the transistor input port for minimum noise figure. (Note: the noise contribution of a device may be expressed as either a noise figure in dB or a noise temperature in K. The relationship between these two measurements is shown in Figure 4.) A graph showing the total amplifier and system noise figures in K as a function of first stage noise figure in dB is shown in Figure 5.

The input network of Q1 is designed to match from a 50 Ω generator to Γ_{on} using lossless elements. Starting at Γ_{on}^* a series impedance of + j36 Ω brings the reflection coefficient to point A in Figure 6. This impedance is realized using a 1.43 nH inductor. Transforming to the admittance plane to point B, we find that an open stub of admittance j1.1 nS (normalized to 20 mS) will complete the match. The length of this stub is 0.132 λg. For a softboard substrate having an effective dielectric constant of 2.05, this translates to a physical length of:

$$I = \frac{0.132c}{f \text{ x} \sqrt{\varepsilon_K}} = \frac{0.132 \text{ x } 3 \text{ x } 10^{10} \text{ cm/sec}}{3.95 \text{ GHz x } 2.54 \text{ cm/in x} \sqrt{2.05}} = 0.275 \text{ in}$$

Thus, the input design is simply a 50 Ω stub 275 mils long followed by an inductor of 1.4 nH. Notice that the series inductor can be realized using the gate lead of the transistor package.

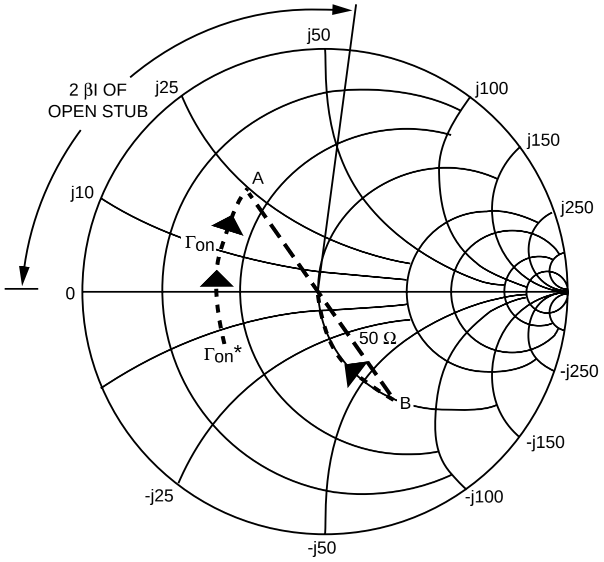


Figure 6. Input Network Design

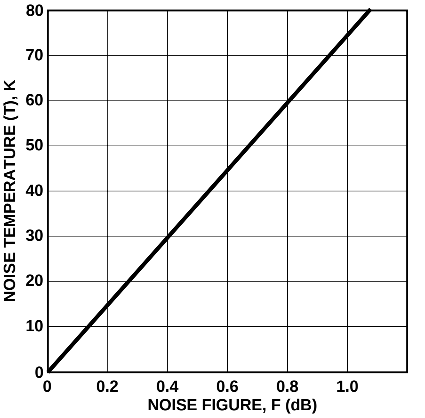


Figure 4. Noise Temperature vs. Noise Figure

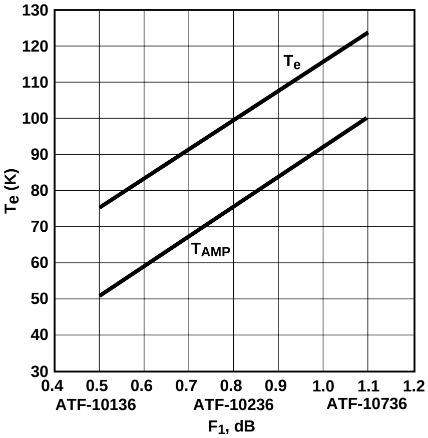


Figure 5. Effective Input Noise Temperature (T_e) vs. First Stage Noise Figure (F_1) (T_{Ant} = 25 K)

```
!ATF-10236      S PARAMETERS      BIAS: Vds=2V, Ids=20mA
!F    M[S11]   A[S11]   M[S21]   A[S21]   M[S12]  A[S12]   M[S22]  A[S22]

2      .74      -78      4.99      107      .09      50      .37     -54
3      .60     -105      4.17       82      .12      38      .34     -57
4      .52     -142      3.65       56      .15      24      .26     -60
5      .47      170      3.12       30      .17       7      .10     -51
6      .53      128      2.62        5      .18      -7      .09      71
7      .63       99      2.18      -15      .19     -20      .22      76
8      .72       77      1.80      -33      .19     -31      .32      67
9      .79       58      1.47      -50      .18     -43      .42      53
10     .80       41      1.19      -67      .18     -47      .49      41
11     .83       31      1.05      -80      .16     -64      .57      34
12     .83       22       .99      -93      .16     -71      .59      28

!NOISE PARAMETERS
!F    FOPT     M[NO]    A[NO]       RN/50

3     0.7      .42      108         .072
4     0.8      .42      148         .072
5     0.95     .42      180         .072
```

Figure 7. S Parameters File for ATF-10236

```
!ATF-10736      S PARAMETERS      BIAS: Vds=2V, Ids=20mA
!F     M[S11]   A[S11]   M[S21]   A[S21]   M[S12]   A[S12]   M[S22]   A[S22]

2       .79      -74      4.48      111      .082      52      .33       -38
3       .65     -108      3.85       85      .108      39      .25       -45
4       .58     -145      3.37       59      .137      26      .15       -4B
5       .54      175      2.90       34      .156      11      .05       -5
6       .57      135      2.4B        9      .173      -3      .11        76
7       .66      103      2.06      -12      .177     -17      .23        70
B       .73       83      1.66      -30      .174     -28      .33        59
9       .80       70      1.37      -45      .166     -37      .44        50
10      .81       57      1.17      -59      .184     -44      .49        48
11      .84       44      1.03      -72      .168     -53      .56        46
12      .85       32       .94      -84      .164     -61      .58        41

!NOISE PARAMETERS
!F   FOPT     M[NO]     A[NO]       RN/50

3     1.0      .43       122         .042
4     1.1      .43       152         .042
5    1.25      .43       180         .042
```

Figure 8. S Parameters File for ATF-10736

The match for Q2 is established in a similar manner using the ATF-10736 S-parameters. The output of Q2 is conjugately matched for best gain, and the interstage between Q1 and Q2 is designed for both gain and stability. Stability of the amplifier should be checked at all frequencies where the stability factor k of the device used is less than 1.0. This means stability should be checked at frequencies below the band of operation as well as across the 3.7 – 4.2 GHz band. The entire match for the FET stages is then optimized using the Touchstone® program (Table 2.)

The noise parameters listed above correspond to a bias point of 2 V at 20 mA. A PNP active bias network (shown in Figure 9) is used to establish this bias point and to ensure that it remains constant over temperature. The bias current is set by R1 for Q1 and by R2 for Q2. A resistive divider sets the drain voltage. A DC converter circuit (shown in Figure 10) is used to provide the -5 volts needed for the gate bias.

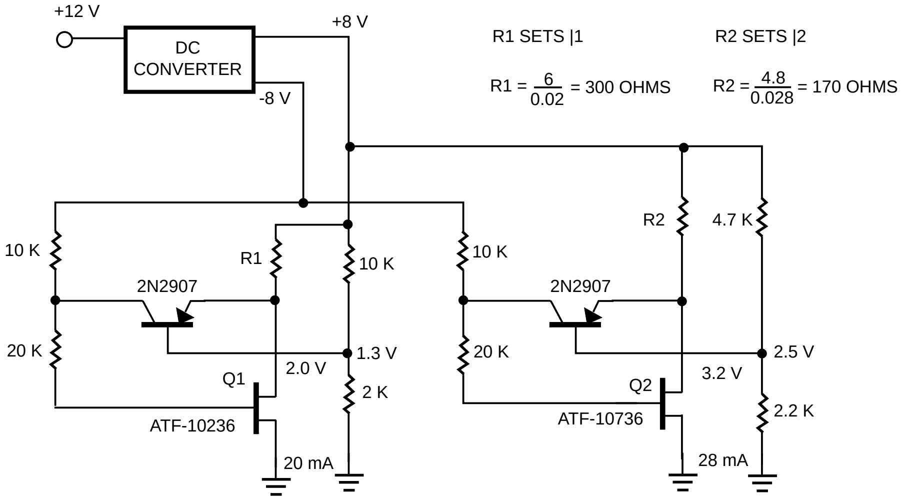


Figure 9. 3.7 – 4.2 GHz Low Noise Amplifier DC Schematic

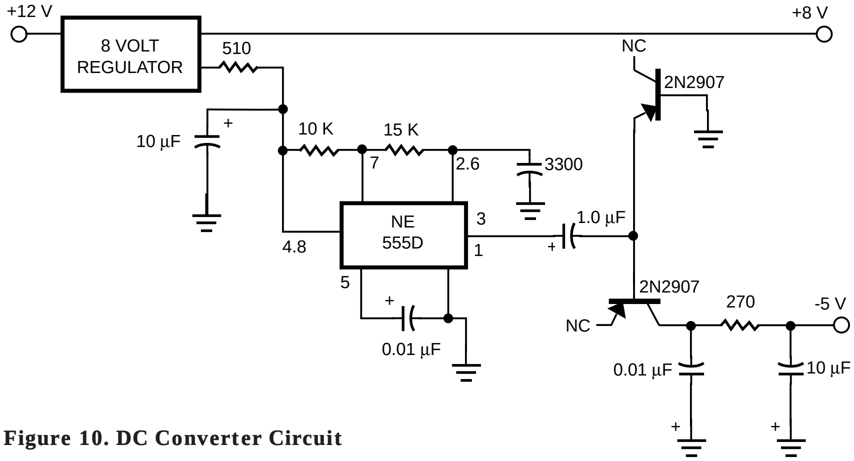


Figure 10. DC Converter Circuit

The bipolar transistor selected for use in stages 3 – 6 is the HP AT-41435. This device provides reasonable gain and noise performance at an economical cost and, like the ATF-10236 and ATF-10736, comes packaged in a glass sealed ceramic package for commercial applications. The first three stages are biased at 15 mA for current efficiency; the output stage is biased at 37 mA for power out. As with the FETs, an active bias circuit using PNP transistors is used to ensure the stability of the bias point over temperature. The DC bias circuit used is shown in Figure 11.

The match for the bipolar stages is established in a similar manner to that of the FET stages. Using the data sheet S-parameters, a single device is conjugately matched to achieve maximum flat gain and minimum reflected power. Two such stages are then cascaded, and the interstage is reoptimized for stability and flat gain. This match is then “step and repeated” until all four stages are incorporated. Remember that the S-parameters used for the first 3 stages use the 8 V, 10 mA data, while the output stage design uses the 8 V, 25 mA data. Once again the design is optimized using the Touchstone program (Table 2).

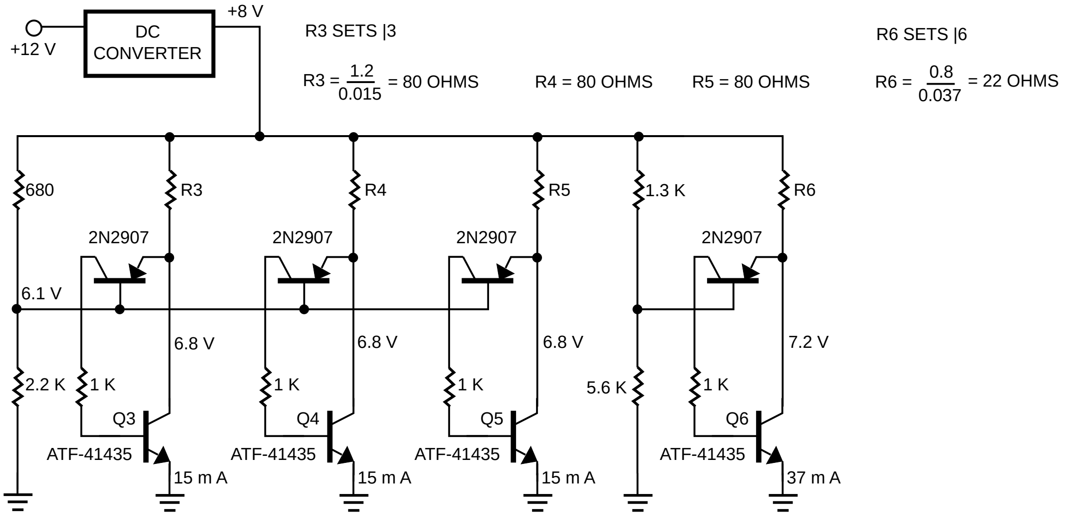


Figure 11. 3.7 - 4.2 GHz Low Noise Amplifier DC Schematic

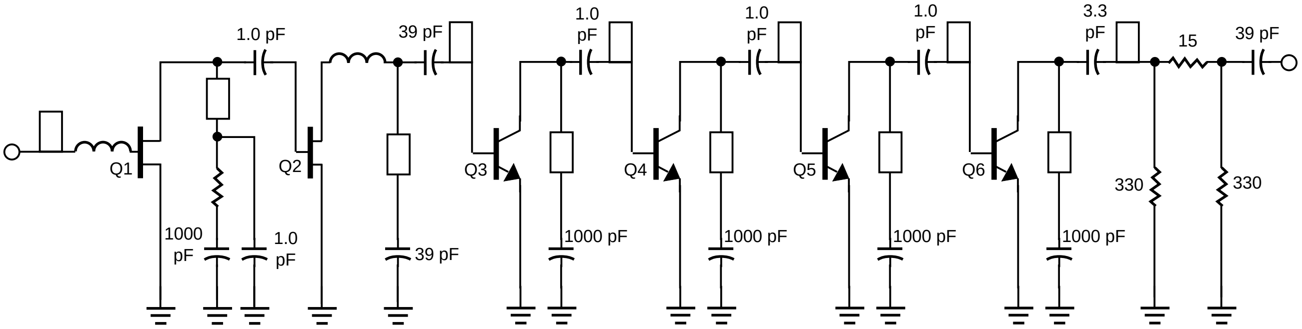


Figure 12. 3.7 - 4.2 GHz Low Noise Amplifier RF Schematic

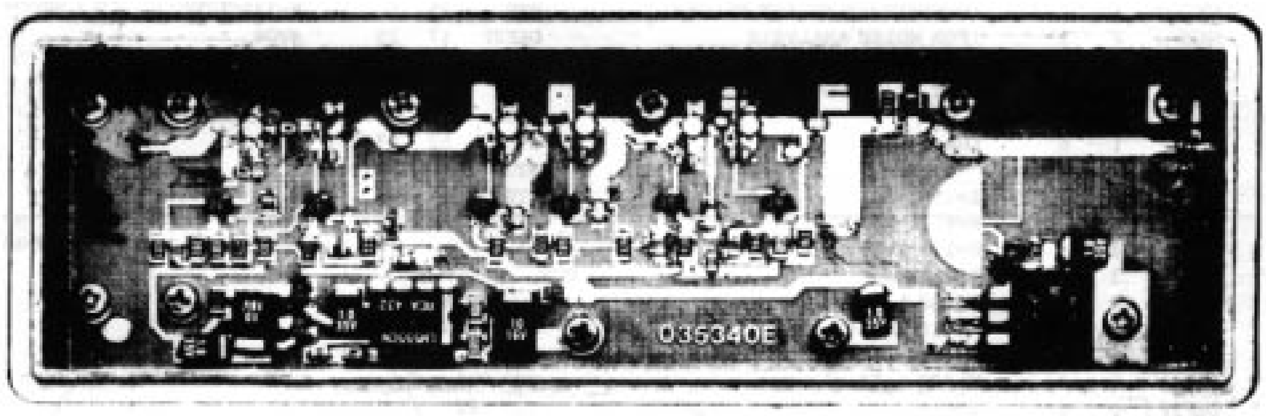


Figure 13. 4 GHz Low Noise Amplifier, Gain = 52 dB

The entire RF schematic for the final LNA is shown in Figure 12. The assembled RF and DC circuits are shown in Figure 13. In this photo the RF input is in the upper left corner, and the RF output and the DC input are in the upper right corner. The upper part of the circuitry is the RF path; the lower portion of the circuit is the DC path.

Performance

The Touchstone file describing the entire LNA is shown in Figure 14. (The S-parameter files ATF-10236 and ATF-10736 are given in Figures 7 and 8, respectively. The S-parameter files AT-41435A and AT-41435B are on the HP product disk supplied with Touchstone.) The predicted performance of the amplifier is shown in Figure 15. This simulation predicts a minimum gain of 54 dB and a maximum noise temperature of 70 K.

```
CKT
    MSUB ER=2.56 H=31 T=1.0 RHO=1.0 RGH=0
    MLIN     1     2            W=80 L=.01        !1ST FET STG
    MLIN     2     3            W=80 L=.01
    MLOC     3                  W=80 L=275
    IND      3     4            L=1.4
    DEF2P    1     4            NAIN
    S2PA     4     5     0      ATF10236
    DEF2P    4     5            NA2P
    MLIN     5     6            W=30 L=80
    MLIN     6     61           W=10 L=250
    SRC      61    0            R=50 C=1000       !2ND FET STG
    SLC      61    0            L=.5 C=1
    SLC      6     7            L=.5 C=1
    MLIN     7     8            W=30 L=40
    DEF2P    5     8            NBIN
    S2PB     8     9     0      ATF10736
    DEF2P    8     9            NB2P
    IND      9     10           L=1.9
    MLIN     10    101          W=20 L=250
    SLC      101    0           L=.5 C=39
    DEF2P    9     10           NBOUT

    NAIN     1     2            !CONNECTION OF FET STAGES
    NA2P     2     3            !FOR NOISE ANALYSIS
    NBIN     3     4            !(NOISE ANALYSIS ON
    NB2P     4     5            !FET STAGES ONLY)
    NBOUT    5     6
    DEFZP    1     6            LNA

    SLC      1     2            L=.5 C=39         !1ST BIPOLAR
    MLIN     2     3            W=80 L=395
    MLOC     3                  W=110 L=135
    S2PC     3     4     0      AT41435A
    MLIN     4     5            W=100 L=55
    MLIN     5     25           W=110 L=150
    SLC      25    0            L=.5 C=1000
    MLIN     5     6            W=100 L=55
    DEF2P    1     6            STG1
    SLC      6     7            L=.5 C=1          !2ND BIPOLAR
    MLIN     7     8            W=65 L=100
    MLOC     8                  W=110 L=135
    S2PC     8     9     0
    MLIN     9     10           W=80 L=80
    MLIN     10    26           W=90 L=200
    SLC      26     0           L=.5 C=1000
    MLIN     10    11           W=80 L=115
    DEF2P     6    11            STG2
    SLC      11    13           L=.5 C=1          !3RD BIPOLAR
    MLIN     13    14           W=80 L=170
    S2PC     14    15    0
    MLIN     15    16           W=80 L=18
    MLIN     16    27           W=35 L=400
    SLC      27    0            L=.5 C=1000
    MLIN     16    17           W=80 L=32
    DEF2P    11    17           STG3
    SLC      17    18           L=.5 C=1          !4TH 8IPOLAR
    MLIN     18    19           W=80 L=65
    MLOC     19                 W=65 L=50
    S2PD     19    20    0      AT41435B
    MLIN     20    21           W=80 L=200
    MLIN     21    28           W=35 L=85
    SLC      28    0            L=.5 C=1000
    SLC      21    22           L=.5 C=3.3
    MLOC     22                 W=125 L=100
    MLIN     22    23           W=80 L=100
    MLSC     23                 W=100 L=500
    MLIN     23    24           W=80 L=175
    RES      24    0            R=330
    RES      24    25           R=15
    RES      25    0            R=330
    DEF2P    17    25           STG4

    LNA      50    51           !CONNECTION OF
    STG1     51    52           !ENTIRE AMPLIFIER
    STG2     52    53
    STG3     53    54
    STG4     54    55
    DEF2P    50    55           TOT

OUT
    TOT D8[S21] GR1
    LNA D8[NF]   GR2
    TOT K
    TOT S11
    TOT S22
FREQ
    SWEEP  1  5  .5
    SWEEP  3.7   4.2  .1
GRID
    GR1   0   70  10
    RANGE   3.5   4.5  .1
    GR2   0  2  ..2
```

Figure 14. Touchstone Description of 4 GHz LNA

```
FREQ-GHz   DB[S21]    DB[NF]        K MAGS [S11]         ANG[S11]  MAG[S22]     ANG[S22]
               TOT       TOT          TOT        TOT          TOT       TOT          TOT

1.00000      8.466     1.654      9.0E+10      0.903      -71.832     0.521       72.499
1.50000     30.748     1. 461     4.9E+07      0.869      - 94.731    0.504      176.117
2.00000     48.475     1.331      1.1E+05      0.825     -119.373     0.470      131.093
2.50000      Sl.910    1.179      1.1E+04      0.682     -147.856     0.429       99.092
3.00000     52.532     1.047      3.4E+03      0.367     -158.040     0.325       67.371
3.50000     52.448     0.964      668.141      0.487     -151.330     0.133       57.614
3.70000     54.221     0.928      240.015      0.561     -172.611     0.124       87.100
3.80000     55.230     0.912      145.879      0.563      171.231     0.154       94.484
3.90000     56.086     0.899       99.250      0.510      150.730     0.195       92.928
4.00000     56.306     0.892       83.601      0.376      128.752     0.234       84.879
4.10000     55.697     0.901       82.668      0.214      118.998     0.263       73.398
4.20000     54.243     0.923       91.025      0.192      137.177     0.274       61.266
4.50000     48.318     1.131      103.915      0.655       45.952     0.263       25.803
5,00000     29.053     2.356      417.708      0.956      -78.409     0.230      -50.487
```

Figure 15. Output of Touchstone Analysis

Figure 16 compares the measured gain performance of a typical assembled amplifier to that predicted by the simulation. Figure 17 compares its noise performance to that of the simulation. Note that the gain of the actual amplifier is between 52 and 54 dB and its noise temperature is between 75 and 80 K. The difference between measured and calculated performance is due primarily to circuit losses, which for the sake of simplicity were assumed to be zero throughout the simulation. Although the figures describe the performance of a typical amplifier, it should be noted that noise performance of less than 65 K across the band has been achieved from this design. Note also that the higher cost HP ATF-10136 GaAs FET with 0.5 dB typical noise figure is available for use in stages 1 and 2 if desired.

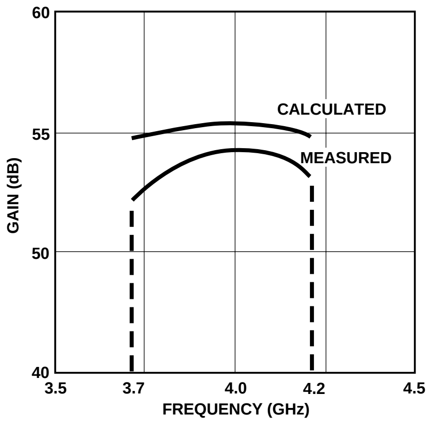


Figure 16. Gain vs. Frequency Low Noise Amplifier

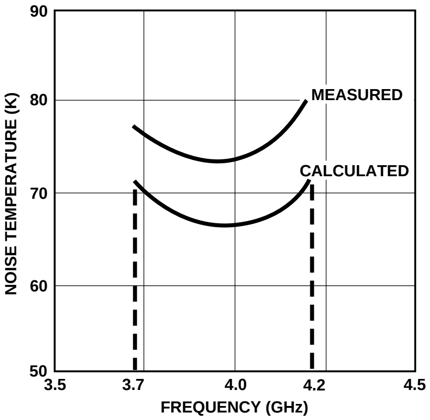


Figure 17. Noise Temperature vs. Frequency Low Noise Amplifier

Appendix 1

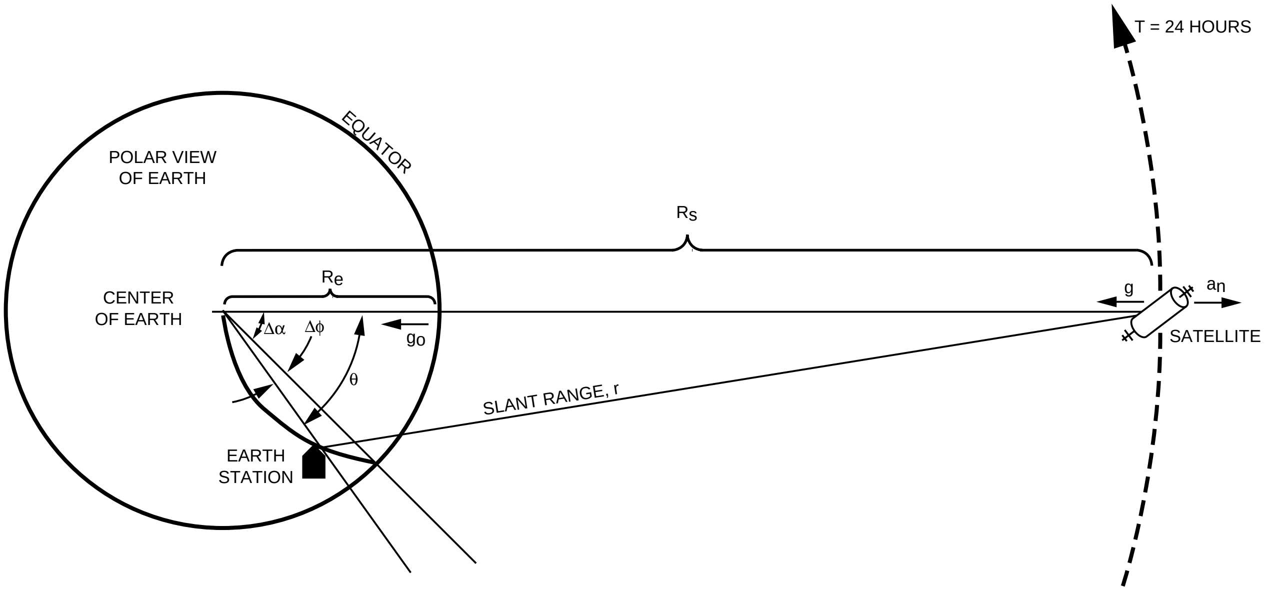


Figure 18. Definitions for Orbiting Satellites

For a satellite in geosynchronous orbit, the sum of the forces acting on the satellite equals zero. Therefore:

$$g + a_n = 0 \qquad \text{Eq. 1}$$

where: g = the pull of gravity on the satellite
a_n = the normal acceleration of the satellite

From mechanics:

$$a_n = \frac{v_s^2}{R_s} \qquad \text{Eq. 2}$$

where: R_s = the distance from the center of the earth to the satellite
v_s = the velocity of the satellite

and

$$V_s = \frac{2\pi R_s}{T} \qquad \text{Eq. 3}$$

where: T = the period of the orbit

Since the pull of gravity decreases inversely by the square of the distance from the earth:

$$g = g_o = \left(\frac{R_e}{R_s}\right)^2 \qquad \text{Eq. 4}$$

where: g_o = the pull of gravity at the earth’s surface
R_e = the radius of the earth

Substituting in equation 1:

$$g_o \left(\frac{R_e}{R_s} \right)^2 - \frac{4\pi^2 R_s}{T^2} = 0$$

Solving for R_s gives:

$$R_s = \sqrt[3]{(g_o T^2 R_e^2)/(4\pi^2)} \qquad \text{Eq. 6}$$

Substituting the values $g_o = 32.2$ ft/sec^2 = 79,036 mi/hr^2

$T = 24$ hours (since the orbit is geosynchronous)
$R_e = 3963$ miles
gives: $R_s = 26{,}270$ miles.

The distance to the satellite in the plane of the equator at the longitude of the satellite is therefore:

$R_s - R_e = 26{,}270 - 3963 = 22{,}307$ miles.

This is the minimum distance from the earth to the satellite.

From trigonometry, the slant range, r, to the satellite is given by:

$$r^2 = R_s^2 + R_e^2 - 2 R_s R_e \mathrm{Cos}\theta \qquad \text{Eq. 7}$$

where θ and r are defined in Figure 18.

As an example, for Satcom 4 satellite at longitude 83° West the calculation for Santa Clara, California is as follows:

Latitude for Santa Clara ≅ 37°.
Longitude for Santa Clara ≅ 122°.

From trigonometry, $\theta \cong 51°$

Therefore:

$$\begin{aligned} r^2 &= 26{,}270^2 + 3963^2 - 2(26{,}270)(3963)(0.6293) \\ &= (690.1 + 15.7 - 131.0) \times 10^6 \\ &= 574.8 \times 10^6 \end{aligned}$$

$$\begin{aligned} r &= 23{,}975 \text{ miles} \\ &= 38{,}559 \text{ km.} \end{aligned}$$

The free space attenuation encountered by a satellite broadcasting from this orbit can be calculated from:

$$L_S = 20 \log \frac{4\pi r}{\lambda} \text{ dB} \qquad \text{Eq. 8}$$

where λ = wavelength

$$\text{at 4 GHz, } \lambda \text{ free space} = \frac{C}{f} = \frac{3 \times 10^8 \text{ m/sec}}{4 \times 10^9 \text{ sec}^{-1}} = 0.075 \text{ meters}$$

L_s is therefore given by:

$$L_s = 20 \log \frac{4\pi(38.559 \times 10^3)}{0.075} \text{ dB}$$

$$= 196.2 \text{ dB}$$

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Obsoletes 5091-8823E

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