HEWLETT®
PACKARD

Low Noise and Moderate Power Amplifiers Using the ATF-21186

Application Note 1064

Introduction

This application note describes the use of a low cost Gallium Arsenide Field Effect Transistor (GaAs FET) designed specifically for the VHF through 2500 MHz frequency range. The Hewlett-Packard ATF-21186, supplied in a low cost 0.085 inch diameter plastic package suitable for surface mount applications, produces noise figures as low as 0.5 dB at 800 MHz. The ATF-21186 is a 750 micron gate width device. Its size makes it fairly easy to match at low frequencies for low noise performance without the customary problem of instability associated with using smaller geometry devices at low frequencies. The device is also capable of producing up to +20 dBm of power at frequencies up to 2.5 GHz.

Typical applications include low noise amplifiers (LNAs) in the 800 to 900 MHz frequency range for use in low current cellular telephone applications and spread spectrum transceiver applications. The ATF-21186 can also be used in LNA applications covering the 1200 to 1600 MHz band for Global Positioning System (GPS) applications. The ATF-21186 also provides low noise preamplification and moderate power output in the 2400 MHz spread spectrum frequency band. This application note addresses the use of this device as an LNA in each of these markets. Performance as a moderate power amplifier is also addressed. The design techniques presented in this application note can also be used to successfully design and build stable low noise amplifiers throughout the VHF through S Band frequency range.

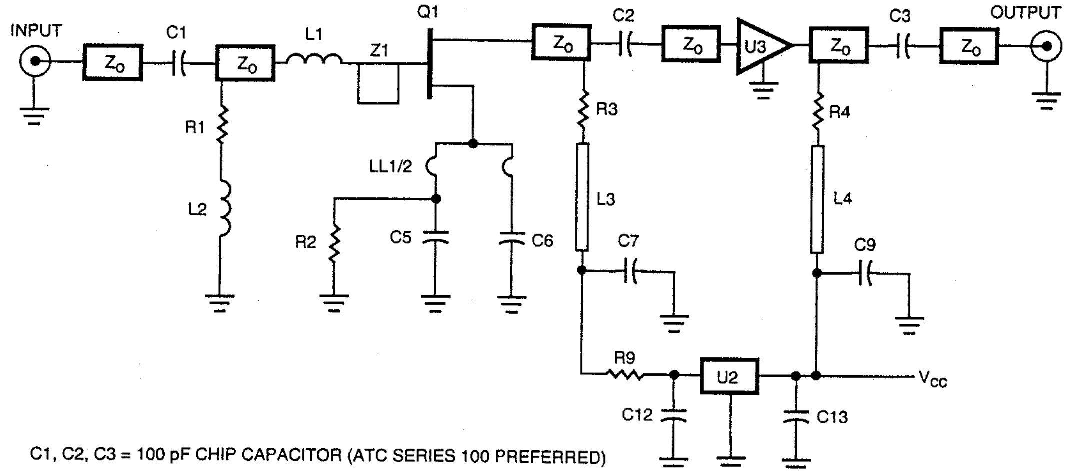
800 to 900 MHz Low Noise Amplifier

Circuit Design

Designing a stable LNA at VHF and L-band frequencies with a GaAsFET requires careful attention to LNA stability at all frequencies where the device has useable gain. An out-of-band oscillation can deteriorate the desired in-band performance, giving the impression of a defective device when in reality there is a circuit design problem. Therefore, stability over the entire frequency range that the device has useable gain is VERY important. From the data sheet S-parameters, this range is from VHF to 8 GHz for the ATF-21186. Design techniques such as resistor stabilization and the use of series feedback in the form of source inductance are mandatory if unconditional stability is desired. General design criteria for low noise FET amplifiers at low frequencies is covered in Reference 1.

A schematic of a suitable LNA for 800 MHz is shown in Figure 1. The schematic shown uses passive biasing. Passive versus active biasing of FETs will be addressed later in this application note. The artwork as shown in Figure 2 can be adapted for either passive or active biasing. The RF circuitry consists mainly of 50 Ω microstripline etched on 0.031 inch thickness printed circuit board material with a dielectric constant of 2.2. The performance of the LNA on low cost epoxy glass material will also be addressed. A parts placement guide is shown in Figure 3. The schematic in Figure 4 shows the additional components required for active biasing.

For the ATF-21186 to produce its rated noise figure, the matching network must transform the customary 50 Ω source impedance to the impedance represented by the reflection coefficient, Gamma Optimum (Γ_0).



C1, C2, C3 = 100 pF CHIP CAPACITOR (ATC SERIES 100 PREFERRED)
C5, C6, C7, C9 = 1000 pF CHIP CAPACITOR (ATC SERIES 700 PREFERRED)
C12, C13 = 0.1 µF CHIP CAPACITOR
L1 = 5 TURNS #24 A.W.G. ENAMEL WIRE, .05" I.D.
L2 = 0.1 µH MINIATURE MOLDED RF CHOKE
L3, L4 = ETCHED MICROSTRIPLINE (SEE TEXT)
LL1, LL2 = 0.040" SOURCE LEAD LENGTH
Q1 = HEWLETT-PACKARD ATF-21186 GaAsFET
R1 = 100 Ω CHIP RESISTOR
R2 = 27 Ω CHIP RESISTOR, ADJUST FOR DESIRED ID
R3, R9 = 50 Ω CHIP RESISTOR
R4 = ADJUST FOR DESIRED MMIC CURRENT
U2 = 5 VOLT REGULATOR, TOKO TK11650U
U3 = HEWLETT-PACKARD MSA-XXXX OR INA-XXXXX SERIES MMIC PROVIDES ADDITIONAL GAIN - OPTIONAL
Z_0 = 50 Ω MICROSTRIPLINE
Z_1 = 0.1" BY 0.1" COPPER TAB POSITIONED AT GATE

Figure 1. ATF-21186 800 MHz Low Noise Amplifier using self biasing.

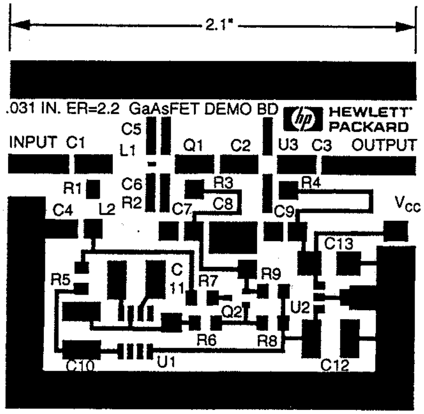


Figure 2. Artwork for the VHF and L Band GaAsFET LNAs using 0.031" D5880/TLY-5.

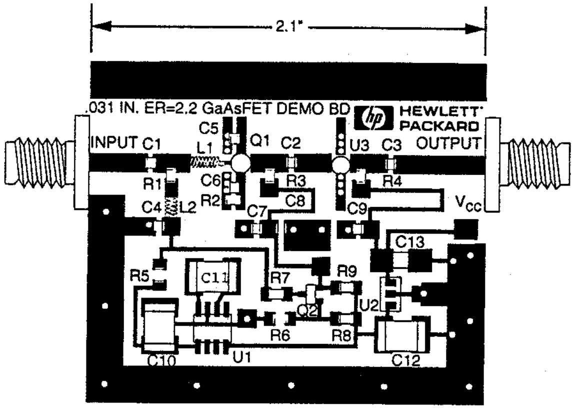
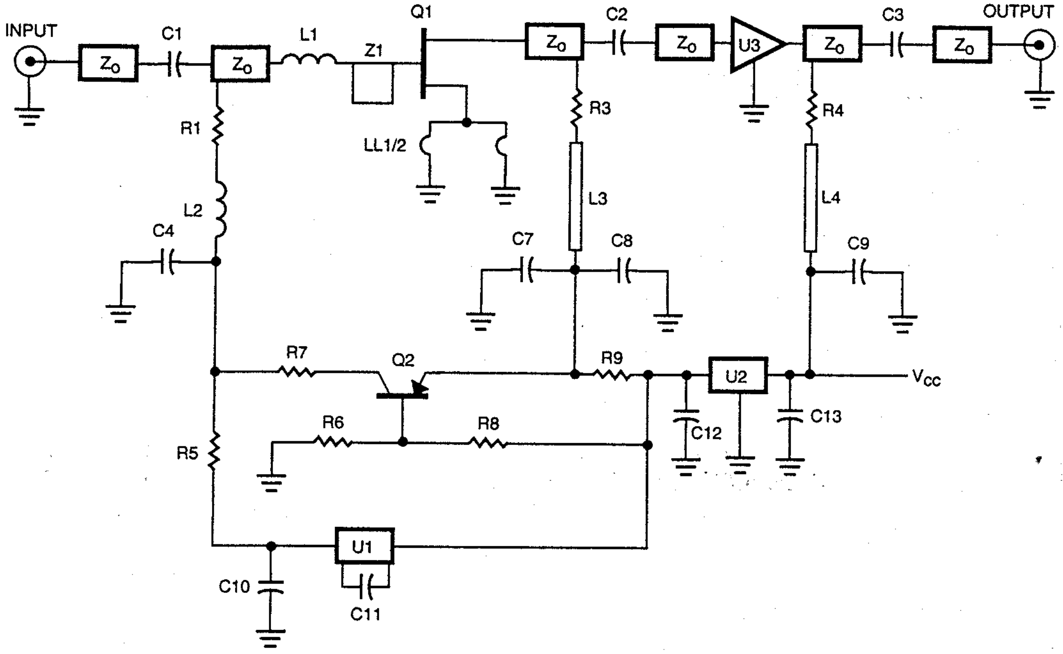


Figure 3. Component placement for the VHF and L Band GaAsFET LNAs.

The noise match is provided by inductor L1 and a small amount of shunt capacitance provided by Z1. The shunt capacitance at the gate consists of a 0.1 x 0.1 inch open circuited stub. For prototyping L1, an air-wound coil consisting of 5 turns #24 gauge enameled wire 0.050 inch inner diameter provides good performance. The turns spacing of L1 can be optimized for a particular frequency. Once the optimum inductance value is determined during the breadboard stage, a commercially available inductor can be substituted. An inductor form with minimum shunt capacitance should be chosen since the capacitance will effect the circuit operation by providing a resonant condition which could effect stability.

Another option is to etch a series high impedance microstripline to replace L1. The microstripline will radiate less than the wound inductor but has the disadvantage of having higher dissipative loss due to the losses of the dielectric material. Typical increase in noise figure would be 0.1 dB on low loss Teflon type materials and several tenths of a dB on FR-4/G-10 epoxy glass materials.

Due to the large amount of tuned gain, i.e. >20 dB, that is available with a FET at 800 MHz, a conjugate match on the output is not



C1, C2, C3 = 100 pF CHIP CAPACITOR (ATC SERIES 100 PREFERRED)
C4, C7, C9 = 1000 pF CHIP CAPACITOR (ATC SERIES 700 PREFERRED)
C5, C6, = NOT REQUIRED, REPLACE WITH COPPER STRAP
C8, C12, C13 = 0.1 µF CHIP CAPACITOR
C10, C11 = 10 µF CHIP CAPACITOR
L1 = 5 TURNS #24A.W.G. ENAMEL WIRE, .05" I.D.
L2 = 0.1 µH MINIATURE MOLDED RF CHOKE
L3, L4 = ETCHED MICROSTRIPLINE (SEE TEXT)
LL1, LL2 = 0.069" SOURCE LEAD LENGTH, INCLUDES COPPER STRAP THAT REPLACES C5 AND C6
Q1 = HEWLETT-PACKARD ATF-21186 GaAsFET
Q2 = SIEMENS SMBT 2907A PNP TRANSISTOR
R1 = 100 Ω CHIP RESISTOR
R2 = NOT REQUIRED

R3 = 50 Ω CHIP RESISTOR
R4 = ADJUST FOR DESIRED MMIC CURRENT
R5, R7 = 10K Ω CHIP RESISTOR
R6 = 1.1K Ω CHIP RESISTOR
R8 = 1K Ω CHIP RESISTOR
R9 = 70 Ω CHIP RESISTOR
U1 = LINEAR TECHNOLOGY LTC1044CS8 VOLTAGE CONVERTER
U2 = 5 VOLT REGULATOR, TOKO TK11650U
U3 = HEWLETT-PACKARD MSA-XXXX OR INA-XXXXX SERIES MMIC PROVIDES ADDITIONAL GAIN - OPTIONAL
Z_0 = 50 Ω MICROSTRIPLINE
Z_1 = 0.1" BY 0.1" COPPER TAB POSITIONED AT GATE

Figure 4. ATF-21186 800 MHz Low Noise Amplifier using active biasing.

desirable from the standpoint of stability. Instead, resistive loading provided by a 50 Ω resistor provides the best overall compromise between gain, output VSWR and stability. A small amount of inductance in the form of L2 is used to raise LNA gain without sacrificing stability. L3 can be either part of the resistor lead when using a 1/4 or 1/8 watt carbon resistor or it can be a 0.45 inch length of 0.020 inch wide microstripline etched on the printed circuit board.

Another concern with any GaAs FET amplifier is excessive gain at frequencies below the frequency of operation, i.e., at 100 to 200 MHz. The incorporation of an L/R network consisting of a 330 nH inductor in series with a 100 Ω resistor in the input network helps establish unconditional stability at the lower frequencies. The 330 nH inductor is used to minimize the effect of the 100 Ω resistor on amplifier noise figure at 800 MHz.

The use of source inductance also plays an important role in optimizing overall LNA performance. In general, adding source inductance between the source of the device and ground has the effect of decreasing the real part of the device's input impedance. This makes Γ_0 and the complex conjugate of S_{11} more nearly equal. The end result can be a better input VSWR when matched for lowest noise figure. Properly chosen, the correct amount of source inductance can also enhance in-band stability. The amount of source inductance that can be added is often limited by its effect on the LNA at other frequencies. An excessive amount of source inductance will produce instabilities at frequencies higher than the normal operating frequency.

The use of passive biasing requires that the FET be self biased by the use of a resistor between the source and ground. The resistor must be bypassed to ground to obtain acceptable RF performance. The inductance associated with the chip bypass capacitor will contribute to the overall source inductance and must be considered in the design. Based on the series resonant frequency of the 1000 pF chip capacitors, a series inductance of 0.4 nH was calculated and used in the computer simulation.

In addition to the inductance associated with the bypass capacitors, the effect of the printed circuit board thickness is taken into account. The source leads are grounded to the bottom side groundplane through the use of vias or plated through holes. The thicker 0.062" printed circuit board will provide greater inductance (2X) than will a thinner 0.031" printed circuit board. The LNA is designed for a printed circuit board thickness of 0.031". Based on the board thickness, the computer simulation suggests 0.040 inch long source leads for best overall LNA performance. This additional length is measured from the edge of the plated through hole to the edge of the flat part of the lead closest to the plastic package and can be constructed using 0.020" wide etched micro-stripline. When direct grounding the source leads as will be done when using active biasing, the source leads can be increased from 0.040" to 0.069" per lead.

Bias Circuitry

It was found empirically that the ATF-21186 provided lowest noise performance at 800 MHz at a drain to source voltage (V_{ds}) of 2 volts and a drain current (I_d) of 25 mA. For simplicity, the original LNA used the self biasing technique for setting the bias point. The 27 Ω resistor between the source and ground sets the drain current while the 47 Ω resistor sets the drain voltage. There is some interaction, however, between the two resistors. The supply voltage is regulated by the 5 volt regulator U2. The disadvantage of the self biasing technique is that variations in Pinchoff Voltage (V_p) and Saturated Drain Current (I_{dss}) that may occur from one production run to another may dictate the need to change the source resistor. The calculation to determine the source resistor R_s is as follows.

$$R_s = [V_p (1 - \sqrt{I_d/I_{dss}})] / I_d$$

Assuming typical device parameters of:

$I_{dss} = 120$ mA
$V_p = -1.5$ volts
and $I_d = 25$ mA
$R_s = 32.6$ ohms

This compares favorably with the 27 Ω resistor used in the actual amplifier.

The preferred alternative in a production environment is the use of an active bias network as described in Figure 4. The typical active biasing scheme for FETs requires that the source leads be grounded and an additional supply be used to generate the negative voltage required at the gate for typical operation. Direct grounding the FET source leads has the additional advantage of not requiring bypass capacitors to bypass a source resistor that would typically be used for self biasing in a single supply circuit. When active biasing is used, the cold end of the 100 ohm resistor in the gate network must be bypassed to ground with a 1000 pF capacitor instead of being dc grounded. This allows gate voltage to be applied.

Although active biasing does add cost by requiring extra components, including a way of generating a negative voltage, the advantages generally outweigh the disadvantages. Active biasing offers the advantage that variations in pinchoff voltage and I_{dss} won't necessitate a change in either the source or drain resistor value for a given bias condition. The active bias network automatically sets V_{gs} for the desired drain voltage and drain current.

Referring to Figure 4, resistors R6 and R8 provide a regulated voltage at the base of Q2. The voltage is increased by 0.7 volts by virtue of the emitter-base junction of Q2 and then applied to the drain of Q1 through resistor R3. Since R3 is included in the RF matching circuit, the voltage drop across R3 must be taken into account when designing the bias circuitry. Resistor R9 is connected between two regulated voltage points and therefore sets the drain current. Q1 gate is connected to a voltage divider consisting of R5 and R7 connected between the collector of Q2 and a negative voltage converter. The gate voltage can then assume a value necessary to sustain the desired drain voltage and current as predetermined by R6, R8, and R9.

Performance

The 800 MHz LNA provides the lowest noise performance at a V_{ds} of 2 volts and $I_d = 25$ mA. The performance of the LNA under these bias conditions is

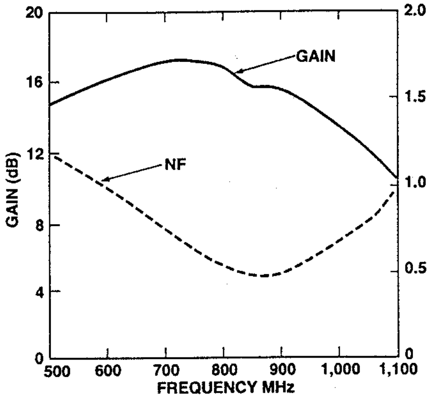


Figure 5. 800 MHz LNA Performance $V_{ds} = 2$ V, $I_d = 25$ mA.

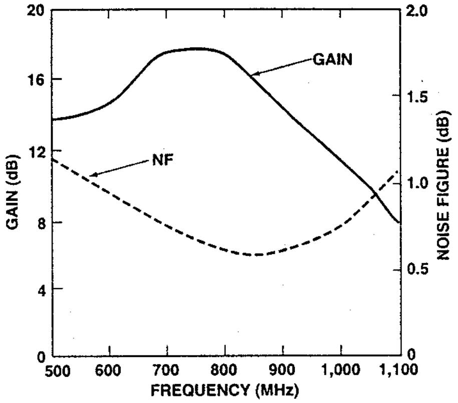


Figure 6. 800 MHz LNA Performance $V_{ds} = 2$ V, $I_d = 10$ mA with output match modification.

shown in Figure 5. The LNA was designed for a center frequency of 850 MHz and provides a nominal 0.55 dB noise figure from 800 to 900 MHz while the gain measured between 15.5 and 16.8 dB. No attempt was made to flatten the gain response. The minimum noise figure at 800 MHz is about 0.05 dB higher at a drain current of 20 mA. According to the data sheet, the ATF-21186 is capable of a typical noise figure of 0.5 dB with an associated gain of 17 dB at 800 MHz at a bias current of 20 mA. Considering that some source inductance is used to improve stability at the expense of gain, the actual performance compares very favorably to the data sheet typical performance. The input circuit losses due to the dielectric material and matching network are on the order of 0.05 to 0.1 dB. The computer simulation shown in Appendix I predicted a noise figure of 0.6 dB with an associated gain of 14 dB. According to the computer simulation, the LNA is not unconditionally stable and it is therefore suggested that the stability circles be plotted at the frequencies where the Rollett stability factor, k, is less than 1. This is easily done with any of the circuit simulation packages. Since the computer does predict lower gain than is actually achieved, one alternative to achieving higher stability is to increase the length of the source leads. Fortunately, due to the large size of the die and corresponding lower high frequency gain, one is able to extend the source lead length out to nearly 0.200 inches and improve low frequency stability without creating stability problems at the higher frequencies.

For applications that are more current conscious, i.e., battery operation, the LNA was tested at a bias current of 10 mA. In order to boost the gain, an additional inductor is placed in series with the drain of the device and the output blocking capacitor. A 2 turn inductor providing approximately 8 nH increased the gain about 1 dB. The resultant performance is shown in Figure 6. The LNA is still able to produce noise figures less than 0.6 dB with 17 dB associated gain.

Although not specifically designed for power applications, the LNA "as is" still provides reasonable power output capability. The use of heavy resistive loading to improve amplifier stability often limits its power output capability. However, the LNA was able to deliver an output P_{1dB} of about +4 dBm at 800 MHz at a bias point of V_{ds} = 2V and I_{ds} = 10 mA. A comparison showing power output and noise figure versus bias conditions is shown in Table I.

Table I. Noise Figure and Output P_{1dB} for 800 MHz LNA at various bias conditions.

V_{ds} (volts)	I_{ds} (mA)	Noise Figure (dB)	P_{1dB} (dBm)	EFF. (%)
2	10	0.60	+4	12.5
3	60	0.76	+15.7	20.8
3	70	0.80	+16.3	20.4

When biased at the power bias condition of V_{ds} = 3 volts and a I_{ds} = 70 mA, the ATF-21186 still provides a 0.80 dB noise figure with a P_{1dB} of greater than +16 dBm making it an excellent candidate for a low noise, high dynamic range LNA. For applications that require greater P_{1dB}, the output matching network can be designed to provide a conjugate match at the frequency of operation. For devices in this power level it is generally sufficient to design the output matching network for a conjugate gain match and still achieve the rated P_{1dB}. For maximum power output it is best to use a minimal amount of resistive loading in the output circuit. Resistive loading will absorb some of the output power. Care should be exercised in assuring that the device is still stable both in-band and out-of-band as the resistive loading is minimized.

The artwork shown in Figure 2 is designed for material with a dielectric constant of 2.2 and a dielectric thickness of 0.031 inch. Computer analysis shows no performance degradation for a dielectric constant varying between 2.0 and 2.5. Suggested materials include Duroid ™ 5880 or Taconics TLY-5. For low cost applications, the familiar G-10 or FR-4 material can also be used with some performance degradation. It is suggested that 0.031" thickness board material be used and simply scale the line widths for the higher dielectric constant. Suggested linewidth for 0.031" FR-4 is 0.058". Artwork designed for 0.031" FR-4 is shown in Figure 7. For 0.062 inch FR-4, the existing artwork can be used as the 50 Ω linewidth is very close to that which is required. Computer analysis predicts only a dB loss in gain and about a tenth of a dB degradation in noise figure when using the same artwork on 0.062 inch thickess FR-4. This is due to the fact that the microstriplines are electrically very short at 800 MHz and have minimal effect on impedance match. Be sure to readjust source lead length as discussed earlier if 0.062" material is used.

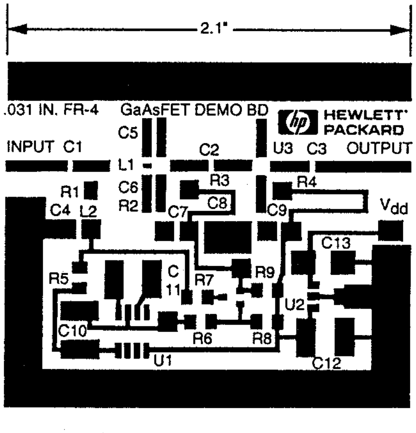


Figure 7. Artwork for the VHF and L Band GaAs FET LNA using 0.031" FR-4/G-10.

The artwork is a general layout intended for breadboarding of prototype circuits in the 450 to 1700 MHz frequency range. The artwork was designed to accommodate the use of an MSA or INA series of monolithic microwave integrated circuit amplifier as a second stage if desired. Suggested devices would include the MSA-0685 or the INA-02184 as examples. A quick calculation using the cascade noise figure equation will indicate the effect of the second stage noise figure of the MMIC on overall LNA noise figure. A sample calculation using the INA-02184 as a second stage follows:

$$NF_{total} = NF1 + \frac{NF2 - 1}{G1}$$

where NF1 = noise figure of first stage

and NF2 = noise figure of second stage

and G1 = gain of first stage

all expressed as ratios

Assume NF1 = 0.6 dB
and G1 = 16 dB
and NF2 = 2.4 dB

Therefore,
converting dBs to ratios:

$$NF_{total} = 1.148 + \frac{1.738 - 1}{39.8}$$

$$= 1.167$$

$$= 0.67 \text{ dB}$$

Assuming a supply voltage of 12 volts, the optimum bias resistor for typical operation of the INA-02184 would be 186 Ω and 531 Ω for the MSA-0686. If the second stage is not desired, then simply bypass the stage by installing a small jumper wire or copper strap which is the same width as the microstripline.

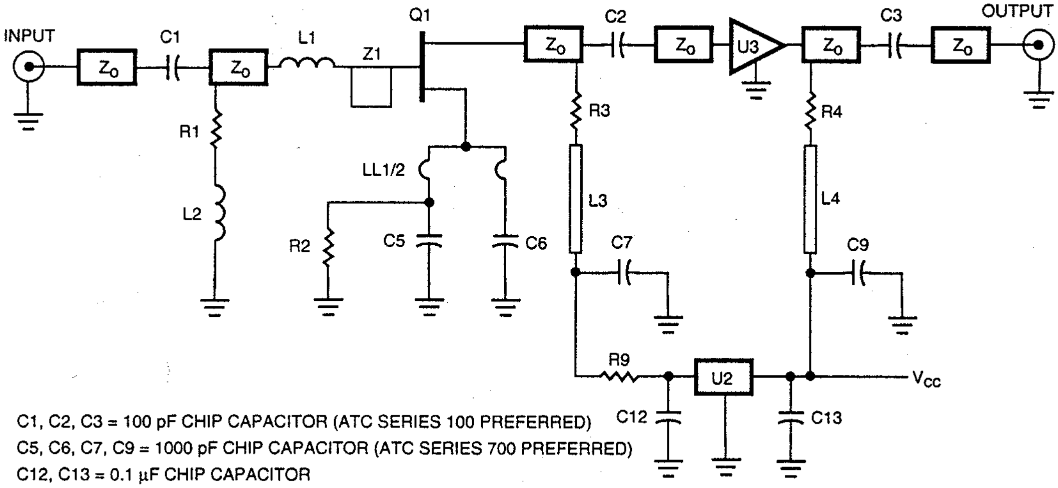
The artwork in Figure 7 is set up to power the MMIC (U3) from 5 V. For 12 volt operation, the etch connecting C9 and R8 should be cut and 12 V applied to capacitor C9.

L Band Low Noise Amplifier

Circuit Design

The ATF-21186 performs very well as a broadband low noise amplifier in the 1 to 2 GHz frequency range. Using similar circuit design techniques to those decribed for the 800 MHz amplifier, noise figures of 0.6 dB are possible over several hundreds of MHz bandwidth. The broad bandwidth of this amplifier makes it very useful for military GPS applications where it is necessary to receive both the 1225 MHz signal and the 1575 MHz signal. The schematic diagram of a typical GPS LNA using passive biasing that has been optimized to cover both GPS frequencies is shown in Figure 8. It is very similar to the 800 MHz amplifier with only minor changes to the input inductor and RF choke. Modification of the bias circuitry for active biasing is similar to that described for the 800 MHz amplifier shown in Figure 4.

For lowest noise performance at 1.5 GHz, it is suggested that the artwork designed for the low loss material as shown in Figure 2 be used. For cost sensitive applications, the artwork shown in Figure 7 designed for 0.031" FR-4/G-10 dielectric material can be used. Noise Figure will be degraded 0.1 to 0.2 dB.



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C5, C6, C7, C9 = 1000 pF CHIP CAPACITOR (ATC SERIES 700 PREFERRED)
C12, C13 = 0.1 µF CHIP CAPACITOR
L1 = WIDE BAND VERSION – 3 TURNS #24 A.W.G. ENAMEL WIRE, .05" I.D.
NARROW BAND VERSION – 2 TURNS #28 A.W.G. ENAMEL WIRE, .05" I.D CLOSE SPACED
L2 = 0.18 µH MINIATURE MOLDED RF CHOKE
L3, L4 = ETCHED MICROSTRIPLINE (SEE TEXT)
LL1, LL2 = 0.040" SOURCE LEAD LENGTH
Q1 = HEWLETT-PACKARD ATF-21186 GaAsFET
R1 = 100 Ω CHIP RESISTOR
R2 = 27 Ω CHIP RESISTOR, ADJUST FOR DESIRED Id
R3, R9 = 50 Ω CHIP RESISTOR
R4 = ADJUST FOR DESIRED MMIC CURRENT
U2 = 5 VOLT REGULATOR, TOKO TK11650U
U3 = HEWLETT-PACKARD MSA-XXXX SERIES MMIC PROVIDES ADDITIONAL GAIN - OPTIONAL
Z_0 = 50 Ω MICROSTRIPLINE
Z_1 = NARROW BAND VERSION ONLY, 0.2" BY 0.2" COPPER TAB POSITIONED AT L1 AND 50 Ω MICROSTRIPLINE

Figure 8. ATF-21186 GPS Low Noise Amplifier using self biasing.

Performance

The performance of the completed amplifier built on 0.031" TLY-5 is shown in Figure 9. As observed with the 800 MHz LNA, the ATF-21186 provides a 0.05 dB lower noise figure at 25 mA versus 20 mA drain current. The LNA provides a 0.65 dB noise figure and 14 dB of associated gain at 1200 MHz and about a 0.8 dB noise figure and 10 dB of associated gain at 1575 MHz. According to the data sheet, the ATF-21186 is capable of a 0.6 dB noise figure and 15 dB of associated gain at 1200 MHz at a drain current of 20 mA. Actual circuit performance is very comparable to the typical values in the data sheet. Loss in noise figure due to dielectric losses and component losses is only a tenth of a dB. Gain is about one dB lower due to the use of resistive loading to enhance amplifier stability. Comparison to the computer simulation shown in Appendix II reveals actual gain at about 1200 MHz to be 2 dB higher than the simulation.

Input return loss varied from 5 dB at 1200 MHz and 6 dB at 1300 MHz to 3.8 dB at 1500 MHz. Output return loss was measured at greater than 10 dB from 800 to 1500 MHz. These results compare favorably to the computer simulation.

Single stage amplifiers are difficult to optimize for both input and output VSWR while still retaining a low noise figure. Adding source inductance does force S_{11}^* to be closer to Γ_o forcing a lower input VSWR when the device is matched for lowest noise figure. There is a limit to how much source inductance one can add without producing stability problems. If lower input VSWR is still desired then noise figure may have to be compromised.

Another option is to design a two stage LNA with intentional impedance mismatching in the interstage network. In addition to source inductance, a forced mismatch at the drain of the first device can also rotate S_{11}^* around to be closer in alignment with Γ_o. The interstage impedance matching network can also be used to enhance stability, leaving the output impedance matching network to provide low output VSWR.

Narrow Band Version

For commercial GPS receivers that only require the reception of the 1575 MHz signal, the input circuit can be modified as shown in Figure 8. Instead of a low Q series inductor match, an L match is used to provide a better noise match over a narrow band. In addition to a slight decrease in noise figure, the match also provides a better impedance match resulting in several dB more gain at 1575 MHz. The performance of the modified GPS LNA is shown in Figure 10. The measured gain of 13 dB is about 2 dB greater than indicated on the computer simulation shown in Appendix II. The measured noise figure of 0.70 dB is 0.05 dB lower than the performance predicted by the computer simulation.

Stability Considerations

It is difficult to obtain broadband unconditional stability with high performance GaAsFET devices at low frequencies without some other performance degradation. Generally a reduction in amplifier gain is traded off for increased stability.

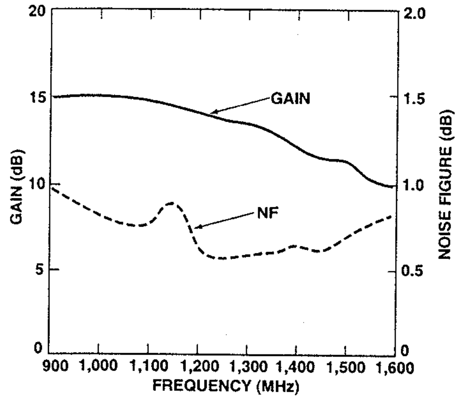


Figure 9. Broad Band GPS ATF-21186 LNA
V_{ds} = 2 V, I_{ds} = 25 mA.

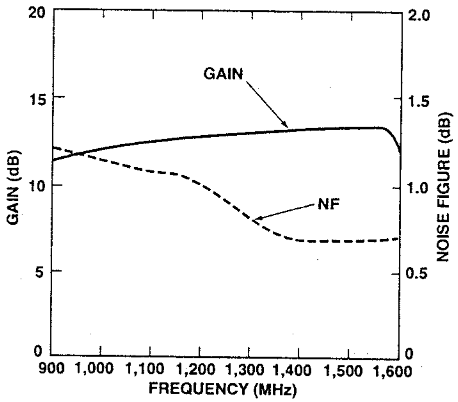


Figure 10. Performance of Modified GPS LNA
V_{ds} = 2 V, I_{ds} = 25 mA.

The primary design goals for the ATF-21186 LNAs described in this note are noise figure and reasonable gain. Computer derived stability circles for both L Band amplifiers are shown in Figures 11 and 12. Frequency span for both plots is 400 MHz to 1900 MHz. Performance of both is similar. For the input stability circles the area outside the circles represents stable load regions while the area inside the output stability circles represents stable load regions. The plots indicate a potential for instability only with an output load that is inductive and greater than about a 3.5:1 VSWR. On the input, unless the VSWR of the antenna is greater than about 14:1, the LNA should remain stable. In situations where the application has a transmission line between the LNA and antenna, merely having 0.6 dB of loss is enough to guarantee that the LNA will not oscillate when the antenna is removed. Stability performance can be improved at the expense of gain by adding more source inductance or series resistance between the drain of the FET and the output matching network. Another alternative is to design a two stage amplifier where the interstage matching network is designed to enhance stability. The bottom line is that the device cannot deliver its rated performance if it is oscillating, even if it is out-of-band.

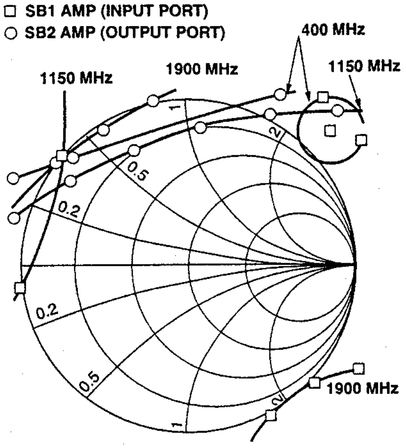


Figure 11. **Input and Output Stability Circles for the broad band GPS LNA.**

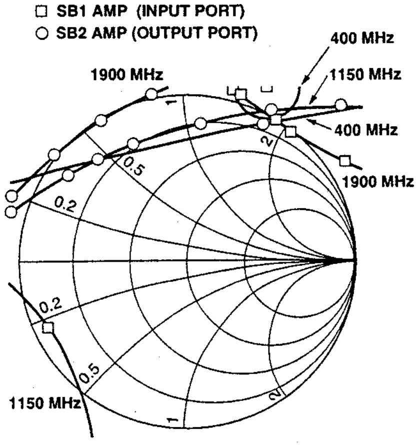
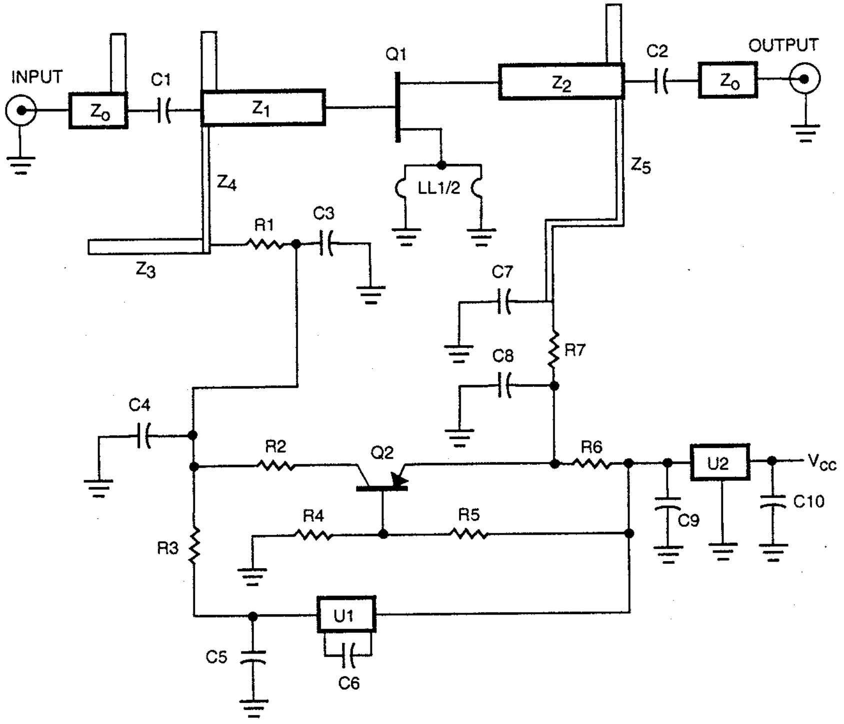


Figure 12. **Input and Output Stability Circles for the narrow band GPS LNA.**



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C5, C6 = 10 μF CHIP CAPACITOR
C9, C10 = 0.1 μF CHIP CAPACITOR
LL1, LL2 = 0.040" SOURCE LEAD LENGTH
Q1 = HEWLETT-PACKARD ATF-21186 GaAsFET
Q2 = SIEMENS SMBT 2907A PNP TRANSISTOR
R1, R7 = 50 Ω CHIP RESISTOR
R2, R3 = 10 K Ω CHIP RESISTOR
R4 = 1.1K Ω CHIP RESISTOR
R5 = 1K Ω CHIP RESISTOR
R6 = 70 Ω CHIP RESISTOR
U1 = LINEAR TECHNOLOGY LTC1044CS8 VOLTAGE CONVERTER
U2 = 5 VOLT REGULATOR, TOKO TK11650U
Z_0 = 50 Ω MICROSTRIPLINE
Z_1, Z_2, Z_3, Z_4, Z_5 = ETCHED MICROSTRIPLINE CIRCUITRY

Figure 13. **ATF-21186 S Band Low Noise Amplifier using active biasing.**

S-Band Low Noise Amplifier

Circuit Design

The ATF-21186 provides a low cost solution for low noise preamplification and moderate power in the 2 to 2.5 GHz frequency range. Using a simple microstripline circuit, the ATF-21186

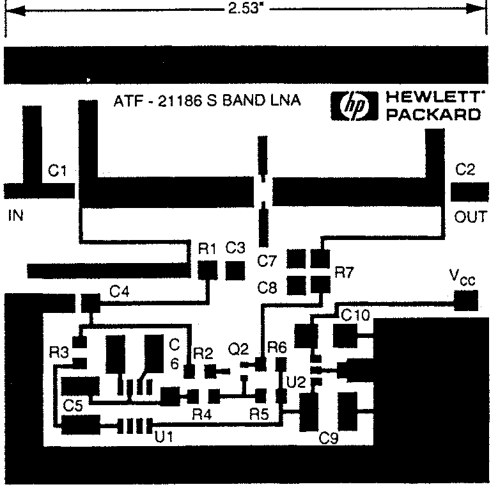

Figure 14. Artwork for the S BandGaAs FET LNA using 0.031" D5880/ TLY-5.

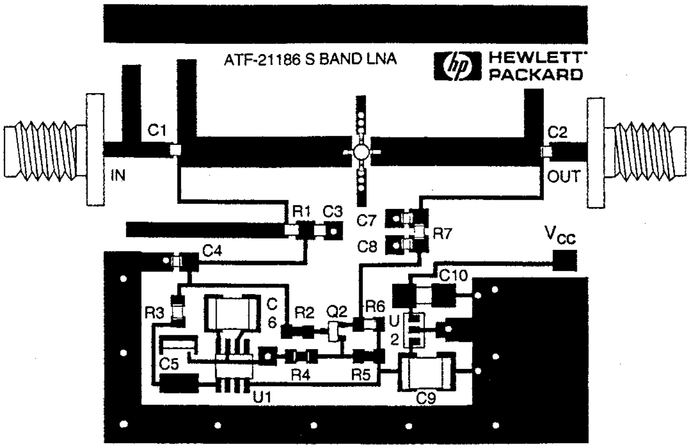

Figure 15. Component Placement for the S Band GaAs FET LNA.

is capable of producing less than 1 dB noise figure and 12 to 13 dB of associated gain. When biased at a V_{ds} of 3 volts and I_d of 70 mA, the ATF-21186 is capable of producing a P_{1dB} of 100 mW without any modifications to the RF matching networks.

The schematic diagram of the S-Band amplifier is shown in Figure 13. The corresponding artwork is shown in Figure 14 along with a component placement guide shown in Figure 15. The RF circuitry incorporates etched microstriplines resulting in a “no-tune” LNA. The input matching network, consisting of a shunt capacitance in the form of open circuited stubs and a series transmission line, matches the device for lowest noise performance. The output matching network provides a conjugate match for maximum associated gain. The design techniques used with the ATF-21186 are similar to those used with the ATF-10136 and the ATF-13284 as described in Hewlett-Packard Application Note AN-G004[2].

A small amount of source inductance in the form of source lead length is used to improve input match and stability at a small sacrifice in gain. Based on a computer analysis to achieve best overall amplifier stability from 100 MHz to 12 GHz, it was determined that the optimum source lead length is 0.040 inches per source lead based on a dielectric material thickness of 0.031 inches.

The use of resistive loading at the drain of the ATF-21186 will also improve in-band stability at the expense of gain. As an example, the use of 5 Ω in series with the drain will raise K from 0.864 to 0.965 at the expense of a gain reduction of 1.1 dB. Computer generated plots showing stability circles of circuits without and with resistive loading in the drain lead are shown in Figures 16 and 17. Swept frequency is from 1.1 to 2.7 GHz. With the series resistance set to 0 Ω, the plots suggest that as long as the input and output VSWR are held to 4.0:1 or less, there will be no stability concerns. However, when using a series resistance of

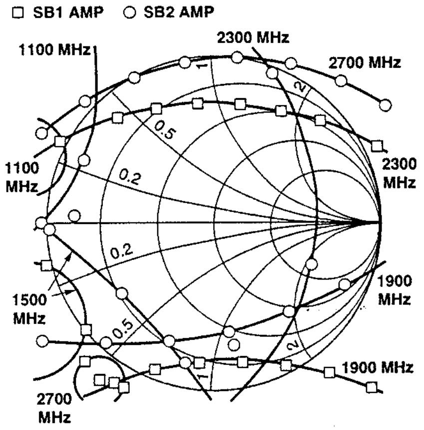

Figure 16. Input and Output Stability Circles for the S Band LNA with drain resistor = 0 Ω (see text).

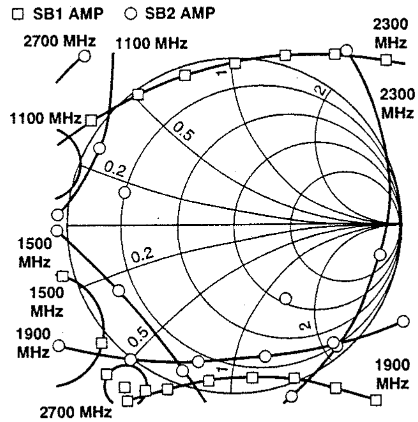

Figure 17. Input and Output Stability Circles for the S Band LNA with drain resistor = 5 Ω (see text).

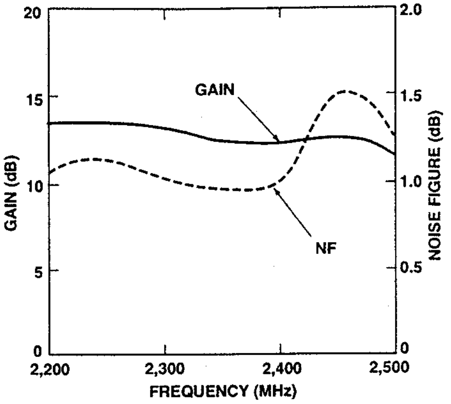

Figure 18. S-Band LNA Performance $V_{ds} = 2$ V, $I_{ds} = 20$ mA.

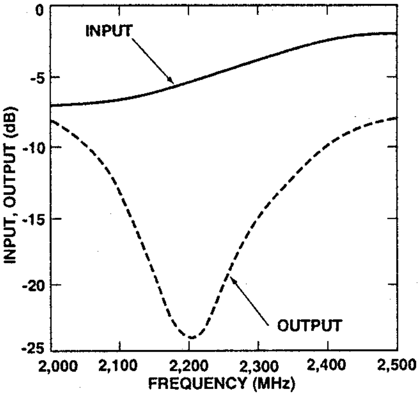

Figure 19. Return Loss for S-Band LNA.

5 Ω, the VSWR can be as high as 7.0:1 and not create any stability concerns.

Quarterwave bias decoupling lines are used to insert the gate and drain voltages. The resistors used at the junction of the high impedance and the low impedance lines provide low frequency loading of the LNA which enhances stability.

Performance

The actual measured gain and noise figure performance is shown in Figure 18. At the bias condition suggested in the data sheet, the LNA provides a 0.94 dB noise figure and 12.2 dB associated gain at 2350 MHz. These results are in fairly close agreement with the computer simulation shown in Appendix III, which suggests a noise figure of 0.8 dB with an associated gain of 12.3 dB. When the device current is raised to 25 mA, the minimum noise figure drops by 0.05 dB. According to the data sheet, the ATF-21186 is capable of a 0.65 dB noise figure and 13 dB of associated gain at 2.3 GHz. The difference in noise figure is due to microstripline and component losses and is considered normal at this frequency. The gain reduction of about 1 dB is a side effect of using source inductance to improve stability.

Input and output return loss are shown in the graph in Figure 19. The computer simulation suggests an input return loss of 7 dB compared to the approximately 5 dB shown in Figure 19. Measured output return loss has a dip at 2200 MHz as compared to 2300 MHz in the simulation. Both input and output return loss measurements suggest that the prototype is probably tuned about a 100 MHz lower in frequency than desired. Input return loss can be improved slightly with some compromises. Adding additional source lead length will improve input return loss at the expense of stability. Trading an increase in noise figure for a better input match is also an alternative. A third alternative is to design a two stage LNA with an intentional mismatch in the interstage matching network. Forcing a mismatch on the output of a single stage LNA will produce a worse output return loss because it no longer presents a conjugate match to the device. A forced mismatch between 2 FET stages can be tuned out such that the return loss looking into the output of the second stage is maintained at an acceptable level.

Without any further output matching, the 2.3 GHz ATF-21186 LNA provides a means of generating moderate power. A P_{1dB} approaching 50% of the dc power input is possible if the drain current is allowed to swing slightly from the quiescent bias point when RF drive is applied at the input.

Active bias was not used during the power tests. At a quiescent drain current of 70 mA, the drain current actually decreases with RF drive level. At lower values of quiescent bias current, the drain current increases with RF drive level.

A quiescent operating point of $V_{ds} = 3$ volts and $I_{ds} = 70$ mA requires 6.5 volts to be applied to the circuit where the emitter of Q2 (reference Figure 13) would normally be attached if active bias were used. When RF drive level is increased to the point where the amplifier is driven to its output P_{1dB}, the drain current decreases to 53 mA causing the drain voltage to increase to 4 volts which is still well under the maximum rating of the device. Under these conditions, a 1dB gain compression point of +20 dBm (referenced to the output) was measured. More output power is possible with increased V_{ds} but the device is limited by the 5 volt V_{ds} breakdown rating.

Other Applications

All three LNAs described earlier can also be quite easily adapted for use as frequency converters. The use of FETs as active mixers is covered in detail in Hewlett-Packard Application Note AN-G005[3]. When used as a down-converter, the RF input of the LNA doubles as the RF input of the mixer. The RF output of the LNA is used to inject LO into the mixer. If the LO is fairly close in frequency to the RF frequency, the output port of the LNA is still fairly well matched at the LO frequency. The IF can then be extracted out of the biasing decoupling line in the drain port. SSB noise figures of 5 to 6 dB and several dB of conversion gain can be expected with the simple modifications as described in AN-G005.

Conclusion

The ATF-21186 is a low cost surface mount solution providing low noise preamplification in the 800 MHz through 2500 MHz frequency range with less than a 1 dB noise figure. The ATF-21186 can also provide a means of generating moderate power (+20 dBm) at frequencies through 2500 MHz.

References

1. A. Ward, "Low-Noise VHF and L-Band GaAsFET Amplifiers", RF Design, February 1989.
2. AN-G004 - Application Note G004, pub. number 5091-9311E.
3. AN-G005 - Application Note G005, pub. number 5091-3744E.

Appendix I. Touchstone™ Circuit File Low Noise Amplifier for Cellular Applications Using the Hewlett-Packard ATF-21186 Low Noise GaAs FET.

```
DIM
     FREQ     GHz
     IND      NH
     CAP      pF
     LNG      IN
VAR
     LL = 0.040    !SOURCE LEAD LENGTH
     CC = 1000    !SOURCE BYPASS CAPACITOR
CKT
     MSUB  ER = 2.2  H = 0.031  T = 0.001  RHO = 1  RGH = 0
     MLIN     1    2     W = 0.080      L = 0.2
     SLC      2    3     L = 0.25       C = 100
     MLIN     3    4     W = 0.080      L = 0.15
     IND      4    5     L = 25
     MLIN     5    7     W = 0.02       L = 0.04
     IND      3    6     L = 100
     RES      6    0     R = 100
     DEF2P    1    7     NAIN

     S2PA     1    2     3  C:\S_DATA\GAAS\21186N20.S2P
     DEF3P    1    2     3  NA2P

     MLIN     1    2     W = 0.020  L^LL
     MLIN     1    3     W = 0.020  L^LL
     SLC      2    4     L = 0.4        C = 1000
     SLC      3    5     L = 0.4        C = 1000
     VIA      4    0     D1 = 0.03  D2 = 0.03  H = 0.031  T = 0.0014
     VIA      5    0     D1 = 0.03  D2 = 0.03  H = 0.031  T = 0.0014
     DEF1P    1          NASER

     MLIN     1    2     W = 0.08       L = 0.1
     IND      2    3     L = 7
     SLC      3    0     L = 0.25       C=4
     IND      2    4     L = 10
     RES      4    5     R = 50
     SLC      5    0     L = 0.4        C = 1000
     SLC      5    0     L = 0.4        C=10000
     MLIN     3    6     W = 0.080      L = 0.1
     SLC      6    7     L = 0.25       C = 100
     MLIN     7    8     W = 0.08       L = 0.1
     DEF2P    1    8     NAOUT

     NAIN     1    2
     NA2P     2    3     4
     NASER    4
     NAOUT    3    5
     DEF2P    1    5  AMP

FREQ
     SWEEP    0.100   12.0  0.1
     !STEP    0.8

OUT
     AMP      DB[S11]
     AMP      DB[S21]
     AMP      DB[S12]
     AMP      DB[S22]
     AMP      K
     AMP      B1
     AMP      DB[NF]
     !AMP     SB1
     !AMP     SB2

OPT
     !AMP     DB[S21]>15
     AMP      K>.4
```

Appendix I. (continued)

FREQ	DB[S11]	DB[S21]	DB[S12]	DB[S22]	K	B1	DB[NF]
GHz	AMP	AMP	AMP	AMP	AMP	AMP	AMP
0.10000	-5.076	7.389	-31.627	-10.010	5.009	1.185	3.876
0.20000	-2.647	10.098	-28.272	-13.643	1.743	1.483	2.673
0.30000	-1.395	12.282	-25.327	-16.925	0.614	1.686	1.962
0.40000	-1.061	14.144	-22.689	-15.914	0.328	1.703	1.504
0.50000	-1.364	15.614	-20.443	-12.532	0.314	1.528	1.178
0.60000	-1.990	16.260	-19.030	-11.407	0.385	1.295	0.878
0.70000	-2.143	15.706	-18.824	-14.421	0.477	1.261	0.690
0.80000	-1.604	14.107	-19.676	-22.679	0.568	1.390	0.622
0.90000	-0.981	11.896	-21.150	-12.931	0.652	1.449	0.680
1.00000	-0.554	9.401	-22.923	-7.735	0.726	1.357	0.860
1.10000	-0.302	6.840	-24.863	-5.017	0.786	1.173	1.187
1.20000	-0.172	4.281	-26.807	-3.401	0.841	0.960	1.640
1.30000	-0.109	1.784	-28.700	-2.381	0.889	0.764	2.196
1.40000	-0.080	-0.623	-30.510	-1.711	0.933	0.599	2.830
1.50000	-0.067	-2.926	-32.226	-1.257	0.972	0.469	3.515
1.60000	-0.063	-5.122	-33.846	-0.943	1.008	0.367	4.230
1.70000	-0.062	-7.217	-35.374	-0.719	1.041	0.290	4.956
1.80000	-0.063	-9.215	-36.816	-0.557	1.072	0.230	5.681
1.90000	-0.064	-11.126	-38.181	-0.437	1.101	0.184	6.397
2.00000	-0.064	-12.957	-39.476	-0.348	1.129	0.148	7.097
2.10000	-0.065	-14.691	-40.749	-0.279	1.158	0.121	7.779
2.20000	-0.065	-16.364	-41.966	-0.226	1.185	0.099	8.440
2.30000	-0.065	-17.983	-43.133	-0.185	1.214	0.081	9.081
2.40000	-0.065	-19.554	-44.257	-0.152	1.243	0.067	9.703
2.50000	-0.065	-21.082	-45.343	-0.127	1.275	0.056	10.307
2.60000	-0.064	-22.572	-46.396	-0.106	1.311	0.047	10.897
2.70000	-0.064	-24.029	-47.422	-0.090	1.352	0.040	11.473
2.80000	-0.064	-25.458	-48.425	-0.076	1.401	0.034	12.041
2.90000	-0.063	-26.862	-49.410	-0.065	1.459	0.029	12.603
3.00000	-0.063	-28.247	-50.380	-0.057	1.530	0.026	13.163
3.10000	-0.062	-29.610	-51.369	-0.049	1.609	0.022	13.724
3.20000	-0.061	-30.961	-52.349	-0.043	1.708	0.020	14.293
3.30000	-0.061	-32.303	-53.326	-0.038	1.835	0.017	14.876
3.40000	-0.060	-33.641	-54.303	-0.034	1.997	0.015	15.479
3.50000	-0.060	-34.979	-55.286	-0.031	2.206	0.014	16.110
3.60000	-0.059	-36.323	-56.281	-0.028	2.479	0.013	16.777
3.70000	-0.059	-37.680	-57.294	-0.026	2.838	0.012	17.490
3.80000	-0.059	-39.056	-58.334	-0.024	3.317	0.011	18.260
3.90000	-0.059	-40.461	-59.409	-0.022	3.967	0.010	19.101
4.00000	-0.059	-41.907	-60.533	-0.021	4.863	0.010	20.026
4.10000	-0.059	-43.446	-61.762	-0.020	6.128	0.009	21.137
4.20000	-0.058	-45.061	-63.071	-0.019	7.975	0.009	22.362
4.30000	-0.058	-46.780	-64.487	-0.018	10.743	0.008	23.728
4.40000	-0.058	-48.639	-66.048	-0.018	15.182	0.008	25.273
4.50000	-0.058	-50.696	-67.810	-0.017	22.637	0.008	27.054
4.60000	-0.058	-53.042	-69.867	-0.017	36.409	0.008	29.163
4.70000	-0.059	-55.842	-72.383	-0.016	65.606	0.008	31.768
4.80000	-0.059	-59.442	-75.705	-0.016	143.283	0.007	35.211
4.90000	-0.059	-64.791	-80.780	-0.016	470.800	0.007	40.443
5.00000	-0.060	-77.368	-93.091	-0.016	999.900	0.007	52.944
5.10000	-0.060	-71.649	-87.114	-0.016	2.1e+03	0.007	47.185
5.20000	-0.061	-64.169	-79.378	-0.015	369.300	0.007	39.702
5.30000	-0.061	-60.527	-75.482	-0.015	155.097	0.007	36.090
5.40000	-0.061	-58.181	-72.886	-0.015	88.167	0.007	33.804
5.50000	-0.062	-56.490	-70.947	-0.015	58.393	0.007	32.195
5.60000	-0.063	-55.190	-69.403	-0.015	42.491	0.007	30.991
5.70000	-0.063	-54.149	-68.121	-0.015	32.782	0.007	30.048
5.80000	-0.06	-53.291	-67.025	-0.015	26.462	0.007	29.271
5.90000	-0.065	-52.565	-66.065	-0.015	22.055	0.007	28.591
6.00000	-0.065	-51.940	-65.210	-0.015	18.826	0.007	27.956
6.10000	-0.066	-51.400	-64.458	-0.015	16.448	0.007	27.685

Appendix I. (continued)

FREQ GHz	DB[S11] AMP	DB[S21] AMP	DB[S12] AMP	DB[S22] AMP	K AMP	B1 AMP	DB[NF] AMP
6.20000	-0.067	-50.925	-63.773	-0.015	14.590	0.007	27.508
6.30000	-0.068	-50.503	-63.144	-0.015	13.072	0.007	27.392
6.40000	-0.068	-50.124	-62.559	-0.015	11.855	0.007	27.311
6.50000	-0.069	-49.780	-62.013	-0.015	10.867	0.007	27.240
6.60000	-0.070	-49.466	-61.499	-0.016	10.020	0.007	27.162
6.70000	-0.071	-49.176	-61.011	-0.016	9.312	0.007	27.069
6.80000	-0.072	-48.906	-60.546	-0.016	8.683	0.007	26.956
6.90000	-0.072	-48.653	-60.100	-0.016	8.139	0.007	26.822
7.00000	-0.073	-48.414	-59.670	-0.016	7.671	0.007	26.670
7.10000	-0.074	-48.173	-59.267	-0.016	7.243	0.007	26.498
7.20000	-0.075	-47.944	-58.878	-0.016	6.865	0.008	26.317
7.30000	-0.076	-47.726	-58.502	-0.017	6.528	0.008	26.128
7.40000	-0.076	-47.517	-58.138	-0.017	6.222	0.008	25.934
7.50000	-0.077	-47.317	-57.783	-0.017	5.947	0.008	25.738
7.60000	-0.078	-47.124	-57.437	-0.018	5.692	0.008	25.541
7.70000	-0.079	-46.937	-57.099	-0.018	5.463	0.008	25.345
7.80000	-0.079	-46.756	-56.769	-0.018	5.254	0.008	25.150
7.90000	-0.080	-46.580	-56.445	-0.019	5.057	0.009	24.958
8.00000	-0.081	-46.410	-56.129	-0.019	4.880	0.009	24.768
8.10000	-0.081	-46.244	-55.819	-0.020	4.712	0.009	24.763
8.20000	-0.082	-46.084	-55.515	-0.020	4.556	0.009	24.766
8.30000	-0.082	-45.929	-55.218	-0.021	4.419	0.009	24.777
8.40000	-0.083	-45.779	-54.928	-0.021	4.281	0.010	24.795
8.50000	-0.083	-45.635	-54.646	-0.022	4.159	0.010	24.821
8.60000	-0.083	-45.498	-54.371	-0.023	4.044	0.010	24.854
8.70000	-0.084	-45.369	-54.106	-0.023	3.936	0.011	24.894
8.80000	-0.084	-45.248	-53.850	-0.024	3.837	0.011	24.941
8.90000	-0.084	-45.136	-53.605	-0.025	3.743	0.011	24.995
9.00000	-0.083	-45.036	-53.372	-0.025	3.655	0.012	25.054
9.10000	-0.083	-44.947	-53.152	-0.026	3.574	0.012	25.120
9.20000	-0.082	-44.873	-52.946	-0.027	3.497	0.012	25.192
9.30000	-0.081	-44.812	-52.757	-0.027	3.423	0.013	25.269
9.40000	-0.080	-44.768	-52.584	-0.028	3.355	0.013	25.352
9.50000	-0.079	-44.742	-52.429	-0.029	3.293	0.013	25.440
9.60000	-0.077	-44.734	-52.294	-0.029	3.233	0.013	25.534
9.70000	-0.075	-44.745	-52.179	-0.030	3.178	0.013	25.632
9.80000	-0.073	-44.775	-52.083	-0.030	3.128	0.014	25.735
9.90000	-0.071	-44.826	-52.009	-0.030	3.078	0.014	25.843
10.0000	-0.068	-44.896	-51.954	-0.030	3.032	0.014	25.955
10.1000	-0.066	-44.986	-51.919	-0.030	2.990	0.014	26.071
10.2000	-0.063	-45.094	-51.902	-0.030	2.951	0.014	26.191
10.3000	-0.060	-45.219	-51.903	-0.030	2.911	0.014	26.314
10.4000	-0.058	-45.360	-51.920	-0.030	2.876	0.013	26.440
10.5000	-0.055	-45.515	-51.951	-0.029	2.844	0.013	26.570
10.6000	-0.052	-45.682	-51.993	-0.029	2.813	0.013	26.703
10.7000	-0.050	-45.859	-52.046	-0.028	2.783	0.013	26.839
10.8000	-0.047	-46.044	-52.106	-0.028	2.760	0.013	26.976
10.9000	-0.045	-46.236	-52.172	-0.027	2.733	0.012	27.117
11.0000	-0.043	-46.431	-52.241	-0.027	2.709	0.012	27.259
11.1000	-0.041	-46.629	-52.311	-0.026	2.684	0.012	27.404
11.2000	-0.039	-46.827	-52.380	-0.026	2.663	0.012	27.550
11.3000	-0.037	-47.023	-52.447	-0.025	2.643	0.011	27.697
11.4000	-0.035	-47.216	-52.508	-0.024	2.622	0.011	27.846
11.5000	-0.034	-47.404	-52.563	-0.024	2.607	0.011	27.997
11.6000	-0.032	-47.584	-52.610	-0.023	2.587	0.011	28.147
11.7000	-0.031	-47.757	-52.646	-0.023	2.573	0.011	28.299
11.8000	-0.030	-47.920	-52.670	-0.023	2.561	0.010	28.452
11.9000	-0.029	-48.072	-52.680	-0.022	2.539	0.010	28.606
12.0000	-0.028	-48.210	-52.674	-0.022	2.528	0.010	28.759

Appendix II. Touchstone™ Circuit File
Broadband Low Noise Amplifier for GPS Applications Using the Hewlett-Packard ATF-21186 Low Noise GaAs FET

```
DIM
     FREQ      GHz
     IND       NH
     CAP       pF
     LNG       IN
VAR
    LL = 0.040     !SOURCE LEAD LENGTH
    CC = 1000      !SOURCE BYPASS CAPACITOR
CKT
     MSUB  ER = 2.2  H = 0.031  T = 0.001  RHO = 1  RGH = 0
     MLIN      1    2     W = 0.080       L = 0.2
     SLC       2    3     L = 0.25        C = 100
     MLIN      3    4     W = 0.080       L = 0.15
     IND       4    5     L = 7
     MLIN      5    7     W = 0.02        L = 0.03
     IND       3    6     L = 100
     RES       6    0     R = 100
     DEF2P     1    7     NAIN

     S2PA      1    2     3  C:\S_DATA\GAAS\21186N20.S2P
     DEF3P     1    2     3  NA2P

     MLIN      1    2     W = 0.020  L^LL
     MLIN      1    3     W = 0.020  L^LL
     SLC       2    4     L = 0.4         C = 1000
     SLC       3    5     L = 0.4         C = 1000
     VIA       4    0     D1 = 0.03  D2 = 0.03  H = 0.031  T = 0.0014
     VIA       5    0     D1 = 0.03  D2 = 0.03  H = 0.031  T = 0.0014
     DEF1P     1          NASER

     MLIN      1    2     W = 0.08        L = 0.1
     RES       2    4     R = 50
     MLIN      4    5     W = 0.02        L = 0.45
     SLC       5    0     L = 0.4         C = 1000
     SLC       5    0     L = 0.4         C= 10000
     MLIN      2    8     W = 0.080       L = 0.1
     DEF2P     1    8     NAOUT

     NAIN      1    2
     NA2P      2    3     4
     NASER     4
     NAOUT     3    5
     DEF2P     1    5  AMP
FREQ
     STEP      1.228
     STEP      1.575
     !SWEEP    0.4  1.9  0.75
     SWEEP     0.100  12.0   0.3
OUT
     AMP       DB[S11]
     AMP       DB[S21]
     AMP       DB[S12]
     AMP       DB[S22]
     AMP       K
     AMP       B1
     AMP       DB[NF]
     !AMP      SB1   GR1
     !AMP      SB2
OPT
     !AMP      DB[S21]>15
```

```
    FREQ      DB[S11]    DB[S21]    DB[S12]    DB[S22]       K         B1      DB[NF]
     GHz        AMP        AMP        AMP        AMP        AMP        AMP       AMP
  0.10000     -5.178      6.872    -32.144    -12.010     6.014      1.219      4.110
  0.40000     -1.155      9.931    -26.902    -13.717     0.848      1.675      2.256
  0.70000     -1.409     11.185    -23.345    -15.875     0.658      1.624      1.615
  1.00000     -2.945     11.969    -20.355    -16.424     0.781      1.360      1.132
  1.22800     -4.410     12.045    -18.873    -14.189     0.855      1.144      0.899
  1.30000     -4.741     11.915    -18.568    -13.403     0.875      1.095      0.845
  1.57500     -4.628     10.779    -18.088    -11.211     0.935      1.042      0.754
  1.60000     -4.532     10.636    -18.088    -11.082     0.940      1.047      0.756
  1.90000     -3.203      8.660    -18.395    -10.190     0.984      1.167      0.939
  2.20000     -2.214      6.618    -18.984     -9.967     1.017      1.309      1.420
  2.50000     -1.613      4.739    -19.522     -9.967     1.040      1.419      2.139
  2.80000     -1.243      3.049    -19.919    -10.060     1.057      1.500      2.996
  3.10000     -1.000      1.570    -20.189    -10.107     1.066      1.555      3.903
  3.40000     -0.830      0.316    -20.346    -10.002     1.066      1.588      4.793
  3.70000     -0.712     -0.802    -20.417     -9.925     1.067      1.611      5.621
  4.00000     -0.627     -1.804    -20.429     -9.893     1.071      1.629      6.353
  4.30000     -0.550     -2.727    -20.434     -9.730     1.063      1.639      7.438
  4.60000     -0.492     -3.578    -20.403     -9.592     1.059      1.646      8.519
  4.90000     -0.446     -4.372    -20.362     -9.501     1.060      1.653      9.586
  5.20000     -0.406     -5.089    -20.298     -9.431     1.053      1.659     10.597
  5.50000     -0.372     -5.772    -20.230     -9.360     1.044      1.664     11.415
  5.80000     -0.340     -6.461    -20.195     -9.321     1.040      1.670     11.678
  6.10000     -0.309     -7.153    -20.211     -9.392     1.036      1.681     11.940
  6.40000     -0.279     -7.847    -20.283     -9.645     1.027      1.702     13.652
  6.70000     -0.250     -8.604    -20.439     -9.982     1.023      1.727     14.453
  7.00000     -0.221     -9.441    -20.698    -10.414     1.026      1.754     14.646
  7.30000     -0.193    -10.307    -21.084    -11.098     1.027      1.789     14.593
  7.60000     -0.167    -11.273    -21.586    -11.872     1.037      1.823     14.548
  7.90000     -0.145    -12.336    -22.201    -12.708     1.058      1.853     14.660
  8.20000     -0.126    -13.478    -22.909    -13.555     1.096      1.879     15.285
  8.50000     -0.112    -14.661    -23.672    -14.342     1.157      1.898     16.158
  8.80000     -0.103    -15.821    -24.423    -14.987     1.245      1.912     17.063
  9.10000     -0.099    -16.863    -25.067    -15.425     1.356      1.921     17.917
  9.40000     -0.098    -17.677    -25.493    -15.629     1.475      1.925     18.616
  9.70000     -0.100    -18.176    -25.609    -15.612     1.571      1.925     19.075
  10.0000     -0.105    -18.338    -25.395    -15.405     1.620      1.921     19.271
  10.3000     -0.112    -18.221    -24.906    -15.040     1.620      1.915     19.258
  10.6000     -0.120    -17.925    -24.237    -14.538     1.584      1.905     19.126
  10.9000     -0.130    -17.545    -23.481    -13.916     1.532      1.892     18.965
  11.2000     -0.140    -17.153    -22.707    -13.200     1.479      1.874     18.840
  11.5000     -0.150    -16.797    -21.957    -12.430     1.432      1.853     18.789
  11.8000     -0.162    -16.502    -21.252    -11.657     1.395      1.827     18.833
  12.0000     -0.170    -16.347    -20.811    -11.166     1.377      1.809     18.919
```

Appendix II. (continued) Touchstone^{TM} Circuit File Narrowband Low Noise Amplifier for GPS Applications Using the Hewlett-Packard ATF-21186 Low Noise GaAs FET

```
DIM
    FREQ     GHz
    IND      NH
    CAP      pF
    LNG      IN

VAR
             LL = 0.04
             CC = 1000

CKT
    MSUB   ER = 2.2  H = 0.031  T = 0.001  RHO = 1  RGH = 0
    MLIN     1     2     W = 0.080     L = 0.2
    SLC      2     3     L = 0.25      C = 100
    MLIN     3     4     W = 0.080     L = 0.15
    MTEE     4     5     6             W1 = 0.08  W2 = 0.02  W3 = 0.2
    MLEF     6           W = 0.2       L = 0.3
    MLIN     5     7     W = 0.02      L = 0.002
    IND      7     8     L = 9
    MLIN     8     9     W = 0.02      L = 0.03
    IND      3     10    L = 100
    RES      10    0     R = 100
    DEF2P    1     9     NAIN

    S2PA     1     2     3  C:\S_DATA\GAAS\21186N20.S2P
    DEF3P    1     2     3  NA2P

    MLIN     1     2     W = 0.020     L^LL
    MLIN     1     3     W = 0.020     L^LL
    SLC      2     4     L = 0.4       C = 1000
    SLC      3     5     L = 0.4       C = 1000
    VIA      4     0     D1 = 0.03     D2 = 0.03  H = 0.031  T = 0.0014
    VIA      5     0     D1 = 0.03     D2 = 0.03  H = 0.031  T = 0.0014
    DEF1P    1           NASER

    MLIN     1     2     W = 0.08      L = 0.1
    RES      2     4     R = 50
    MLIN     4     5     W = 0.02      L = 0.45
    SLC      5     0     L = 0.4       C = 1000
    SLC      5     0     L = 0.4       C = 10000
    MLIN     2     8     W = 0.080     L = 0.1
    DEF2P    1     8     NAOUT

    NAIN     1     2
    NA2P     2     3     4
    NASER    4
    NAOUT    3     5
    DEF2P    1     5  AMP

FREQ
    !STEP    1.575
    SWEEP    .4  1.9  .75
    !SWEEP   .100 12.0  .3

OUT
    !AMP  DB[S11]
    !AMP  DB[S21]
    !AMP  DB[S12]
    !AMP  DB[S22]
    !AMP  K
    !AMP  B1
    !AMP  DB[NF]
    AMP  SB1
    AMP  SB2

OPT
    AMP  DB[S21]>15
```

Appendix II. (continued)

FREQ GHz	DB[S11] AMP	DB[S21] AMP	DB[S12] AMP	DB[S22] AMP	K AMP	B1 AMP	DB[NF] AMP
0.10000	-4.915	6.883	-32.133	-12.024	5.839	1.236	4.107
0.40000	-0.968	9.922	-26.911	-13.628	0.737	1.705	2.247
0.70000	-1.204	10.950	-23.580	-15.803	0.615	1.660	1.669
1.00000	-2.632	11.699	-20.625	-17.627	0.769	1.415	1.223
1.30000	-5.099	12.079	-18.404	-14.762	0.875	1.088	0.907
1.57500	-6.311	11.434	-17.433	-11.074	0.938	0.903	0.714
1.60000	-6.214	11.312	-17.411	-10.818	0.943	0.900	0.705
1.90000	-3.754	9.087	-17.967	-8.900	0.987	1.032	0.795
2.20000	-1.873	6.010	-19.592	-8.417	1.023	1.284	1.486
2.50000	-0.965	2.723	-21.538	-8.499	1.055	1.476	2.994
2.80000	-0.534	-0.490	-23.457	-8.762	1.094	1.595	5.193
3.10000	-0.316	-3.506	-25.265	-8.988	1.142	1.664	7.731
3.40000	-0.199	-6.276	-26.938	-9.043	1.201	1.698	10.319
3.70000	-0.134	-8.873	-28.487	-9.092	1.287	1.719	12.806
4.00000	-0.095	-11.315	-29.940	-9.155	1.408	1.733	15.121
4.30000	-0.070	-13.652	-31.360	-9.087	1.562	1.736	17.830
4.60000	-0.054	-15.895	-32.720	-9.020	1.775	1.736	20.465
4.90000	-0.043	-18.072	-34.062	-8.981	2.074	1.737	23.037
5.20000	-0.036	-20.186	-35.395	-8.959	2.481	1.738	25.528
5.50000	-0.031	-22.307	-36.764	-8.933	3.075	1.737	27.827
5.80000	-0.027	-24.513	-38.247	-8.929	4.028	1.738	29.592
6.10000	-0.024	-26.867	-39.926	-9.025	5.688	1.744	31.503
6.40000	-0.023	-29.477	-41.912	-9.296	8.935	1.760	35.220
6.70000	-0.022	-32.602	-44.437	-9.642	16.551	1.778	38.402
7.00000	-0.023	-36.719	-47.975	-10.076	40.362	1.799	41.854
7.30000	-0.024	-43.235	-54.012	-10.736	181.051	1.826	47.418
7.60000	-0.026	-77.492	-87.805	-11.476	999.900	1.852	80.634
7.90000	-0.028	-44.423	-54.288	-12.271	265.329	1.875	46.594
8.20000	-0.032	-38.861	-48.292	-13.081	80.882	1.895	40.533
8.50000	-0.038	-35.769	-44.779	-13.852	44.247	1.909	37.162
8.80000	-0.044	-33.603	-42.205	-14.527	30.243	1.920	34.769
9.10000	-0.052	-31.824	-40.028	-15.054	22.706	1.926	32.827
9.40000	-0.062	-30.149	-37.964	-15.406	17.444	1.929	31.058
9.70000	-0.073	-28.426	-35.860	-15.573	13.166	1.929	29.316
10.0000	-0.085	-26.630	-33.688	-15.562	9.645	1.926	27.576
10.3000	-0.098	-24.844	-31.528	-15.376	6.949	1.921	25.917
10.6000	-0.109	-23.192	-29.503	-15.015	5.054	1.914	24.458
10.9000	-0.118	-21.771	-27.707	-14.488	3.803	1.903	23.291
11.2000	-0.127	-20.621	-26.174	-13.821	3.006	1.890	22.445
11.5000	-0.135	-19.727	-24.887	-13.070	2.506	1.872	21.899
11.8000	-0.143	-19.051	-23.801	-12.303	2.194	1.851	21.607
12.0000	-0.150	-18.699	-23.163	-11.818	2.054	1.835	21.530

Appendix III. Touchstone^{TM} Circuit File
2.3 GHz LNA Using the Hewlett-Packard ATF-21186 Low Noise GaAs FET

```
DIM
    FREQ      GHz
    IND       NH
    CAP       pF
    LNG       IN

VAR
    LL = 0.04                    !EACH SOURCE LEAD LENGTH
    W1 = 0.15                    !Z1-INPUT SERIES TRANSMISSION LINE
    W2 = 0.15                    !Z4-OUTPUT SERIES TRANSMISSION LINE
CKT
    MSUB                                     ER = 2.2  H = 0.031  T = 0.0007  RHO = 1  RGH = 0
    TAND                                     TAND = 0.001
    MLIN      1     2                        W = 0.094  L = 0.1
    MTEE      2     3     4                  W1 = 0.094  W2 = 0.094  W3 = 0.094
    MLIN      3           5                  W = 0.094  L = 0.18
    MLEF      4                              W = 0.094  L\0.11230
    SLC       5           6                  L = 0.25  C = 10
    MLIN      6           7                  W = 0.094  L = 0.005
    MCROS     7     8     9   10             W1 = 0.1   W2 = 0.1   W3^W1  W4 = 0.020
    MLEF      8                              W = 0.1  L\0.64590
    MLIN      9     11                       W^W1  L = 0.80
    MLIN      10    12                       W = 0.020  L = 0.87
    MLEF      12                             W = 0.1  L = 0.87
    SRL       12    13                       R = 50   L = 0.5
    SLC       13    14                       L = 0.4  C = 1000
    VIA       14          0                  D1 = 0.03  D2 = 0.03   H = 0.031   T = 0.0007
    MSTEP     11    16                       W1^W1   W2 = 0.020
    MLIN      16    17                       W = 0.020  L = 0.002
    DEF2P     1     17                       NAIN

    S2PA      1     2     3                  C:\S_DATA\GAAS\21186N20.S2P

    DEF3P     1     2     3                  NA2P

    MLIN      1     2                        W = 0.020   L^LL
    VIA       2     0                        D1 = 0.03  D2 = 0.03  H = 0.031  T = 0.0007
    MLIN      1     3                        W = 0.020  L^LL
    VIA       3     0                        D1 = 0.03  D2 = 0.03  H = 0.031  T = 0.0007
    DEF1P     1                              NASER

    MLIN      1     2                        W = 0.020   L = 0.002
    MSTEP     2     20                       W1 = 0.020  W2 = 0.1       !RESISTIVE
    MLIN      20    21                       W = 0.1    L = 0.1         !LOADING FOR
    SRL       21    3                        R = 5    L = 0.1           !STABILITY
    MLIN      3     4                        W^W2   L = 0.75
    MCROS     4     5     6    7             W1^W2   W2 = 0.1  W3 = 0.094  W4 = 0.020
    MLEF      5                              W = 0.1   L\0.37688
    MLIN      6     8                        W = 0.094  L = 0.005
    SLC       8     9                        L = 0.25    C = 10
    MLIN      9     10                       W = 0.095  L = 0.3
    MLIN      7     11                       W = 0.020  L = 0.87
    SLC       11    12                       L = 0.25   C = 10
    VIA       12    0                        D1 = 0.03  D2 = 0.03  H = 0.031  T = 0.0007
    SRL       11    13                       R = 50   L = 0.5
    SLC       13    14                       L = 1   C =1000
    SLC       13    14                       L = 1   C = 100000
    VIA       14    0                        D1 = 0.03  D2 = 0.03  H = 0.031  T = 0.0007
    DEF2P 1   10    NAOUT

    NAIN      1     2
    NA2P      2     3    4
    NASER     4
    NAOUT     3     5
    DEF2P     1     5                        AMP

OUT
    AMP       DB[S11]
    AMP       DB[S21]
    AMP       DB[S12]
    AMP       DB[S22]
    AMP       K
    AMP       B1
    AMP       DB[NF]
    !AMP      SB1
    !AMP      SB2

FREQ
    SWEEP     0.1   2.1   0.3
    SWEEP     2.1   2.7   0.1
    SWEEP     2.7   12    0.3
    !SWEEP    1.1   2.7   0.4

OPT
    AMP       DB[S21]>12
    AMP       DB[NF]<0.8
```

Appendix III. (continued)

R = 0 Ω

FREQ GHz	DB[S11] AMP	DB[S21] AMP	DB[S12] AMP	DB[S22] AMP	K AMP	B1 AMP	DB[NF] AMP
0.10000	-0.982	-11.240	-50.476	-0.723	19.643	0.274	13.798
0.40000	-3.741	-3.199	-40.024	-3.147	21.787	0.730	8.133
0.70000	-2.820	5.522	-29.121	-13.168	3.574	1.431	6.156
1.00000	-1.982	7.516	-25.110	-8.494	0.985	1.457	4.651
1.30000	-1.251	7.223	-23.766	-5.835	0.579	1.306	3.784
1.60000	-1.144	7.202	-22.223	-4.466	0.643	1.057	3.170
1.90000	-1.794	8.814	-19.114	-3.968	0.743	0.744	2.267
2.10000	-4.004	11.308	-15.742	-5.210	0.793	0.445	1.465
2.20000	-7.134	12.520	-14.139	-8.311	0.816	0.350	1.082
2.30000	-7.164	12.370	-13.900	-17.801	0.840	0.559	0.815
2.40000	-3.328	10.276	-15.607	-11.798	0.865	0.931	0.798
2.50000	-1.578	7.338	-18.160	-7.682	0.896	1.144	1.199
2.60000	-0.865	4.375	-20.740	-6.223	0.934	1.239	2.163
2.70000	-0.532	1.533	-23.202	-5.686	0.987	1.297	3.746
3.00000	-0.153	-8.231	-31.838	-6.332	1.628	1.502	12.793
3.30000	-0.121	-13.875	-36.545	-8.818	3.721	1.715	19.518
3.60000	-1.154	-2.477	-24.220	-4.539	1.383	1.169	7.980
3.90000	-3.689	-0.968	-21.805	-1.406	1.485	0.337	4.060
4.20000	-9.262	-2.700	-22.716	-0.829	1.752	0.160	3.842
4.50000	-12.358	-5.672	-24.900	-0.497	1.723	0.114	4.538
4.80000	-12.280	-6.261	-24.714	-0.414	1.404	0.102	3.674
5.10000	-1.755	-5.422	-23.141	-1.348	1.401	0.429	4.316
5.40000	-1.017	-24.215	-41.248	-0.061	3.452	0.024	7.555
5.70000	-2.601	-14.378	-30.729	-0.160	1.850	0.052	5.431
6.00000	-4.180	-12.050	-27.732	-0.337	2.203	0.104	6.280
6.30000	-3.365	-8.285	-23.375	-0.770	1.673	0.237	6.639
6.60000	-7.268	-2.121	-16.628	-2.038	1.181	0.476	4.488
6.90000	-15.263	0.696	-13.239	-2.369	1.067	0.337	2.073
7.20000	-9.860	2.156	-11.270	-3.224	1.032	0.325	1.830
7.50000	-4.804	2.601	-10.353	-18.899	1.017	1.141	3.894
7.80000	-0.967	-1.775	-14.268	-5.204	1.011	1.078	5.826
8.10000	-0.439	-5.392	-17.434	-2.991	1.005	0.851	6.967
8.40000	-0.443	-6.416	-18.018	-3.022	0.991	0.884	7.488
8.70000	-1.196	-3.669	-14.838	-6.913	0.965	1.364	7.145
9.00000	-1.182	-5.972	-16.716	-0.664	0.981	0.140	7.340
9.30000	-0.200	-17.466	-27.792	-1.242	1.864	0.477	15.751
9.60000	-0.050	-31.932	-41.844	-8.312	24.250	1.695	32.647
9.90000	-0.091	-35.819	-45.320	-0.985	24.793	0.401	29.051
10.2000	-0.202	-27.325	-36.415	-0.788	5.953	0.324	20.106
10.5000	-0.740	-15.832	-24.512	-2.201	3.001	0.738	13.711
10.8000	-2.175	-10.764	-19.027	-6.169	4.455	1.228	12.591
11.1000	-0.780	-14.359	-22.199	-10.533	4.953	1.676	16.305
11.4000	-6.353	-1.624	-9.029	-15.018	1.330	1.157	7.824
11.7000	-0.564	-10.094	-17.049	-1.670	1.167	0.536	5.152
12.0000	-0.220	-15.877	-22.360	-1.461	1.229	0.541	8.615

Appendix III. (continued)

R = 5 Ω

FREQ GHz	DB[S11] AMP	DB[S21] AMP	DB[S12] AMP	DB[S22] AMP	K AMP	B1 AMP	DB[NF] AMP
0.10000	-0.976	-11.601	-50.837	-0.745	21.717	0.282	13.841
0.40000	-3.685	-3.682	-40.506	-3.199	24.351	0.742	8.225
0.70000	-2.820	5.129	-29.515	-13.830	3.925	1.443	6.185
1.00000	-1.976	7.175	-25.451	-8.600	1.097	1.456	4.670
1.30000	-1.285	6.842	-24.147	-5.733	0.673	1.282	3.805
1.60000	-1.258	6.800	-22.625	-4.384	0.747	1.030	3.191
1.90000	-2.129	8.350	-19.578	-4.041	0.856	0.741	2.292
2.10000	-4.973	10.621	-16.428	-5.663	0.913	0.522	1.500
2.20000	-9.057	11.594	-15.065	-9.344	0.939	0.508	1.128
2.30000	-8.330	11.299	-14.971	-26.245	0.965	0.730	0.876
2.40000	-3.772	9.343	-16.540	-12.773	0.995	1.026	0.879
2.50000	-1.807	6.608	-18.890	-8.082	1.029	1.188	1.301
2.60000	-0.985	3.791	-21.324	-6.451	1.072	1.262	2.281
2.70000	-0.594	1.043	-23.692	-5.831	1.131	1.311	3.870
3.00000	-0.158	-8.571	-32.178	-6.424	1.828	1.511	12.895
3.30000	-0.121	-14.117	-36.787	-9.321	4.073	1.743	19.594
3.60000	-1.161	-2.642	-24.386	-4.942	1.560	1.220	8.050
3.90000	-3.746	-1.129	-21.967	-1.585	1.673	0.377	4.146
4.20000	-9.536	-2.961	-22.977	-0.930	1.989	0.185	3.944
4.50000	-12.068	-6.137	-25.364	-0.548	2.028	0.129	4.670
4.80000	-10.661	-7.645	-26.098	-0.393	1.762	0.100	3.890
5.10000	-2.615	-6.962	-24.682	-1.248	2.270	0.381	4.790
5.40000	-1.470	-25.035	-42.068	-0.060	5.257	0.023	8.096
5.70000	-2.786	-14.907	-31.259	-0.162	2.193	0.052	5.601
6.00000	-4.186	-12.407	-28.089	-0.346	2.516	0.106	6.418
6.30000	-3.384	-8.565	-23.655	-0.787	1.869	0.240	6.730
6.60000	-7.235	-2.357	-16.864	-2.124	1.310	0.487	4.572
6.90000	-15.075	0.526	-13.409	-2.695	1.179	0.390	2.210
7.20000	-9.675	1.890	-11.537	-3.850	1.135	0.428	2.002
7.50000	-4.855	2.096	-10.858	-25.383	1.113	1.183	4.021
7.80000	-1.103	-2.166	-14.659	-5.042	1.099	1.057	5.916
8.10000	-0.519	-5.707	-17.750	-2.889	1.087	0.826	7.041
8.40000	-0.505	-6.758	-18.360	-2.888	1.067	0.853	7.569
8.70000	-1.218	-4.262	-15.431	-6.272	1.038	1.313	7.298
9.00000	-1.196	-6.286	-17.030	-1.157	1.060	0.323	7.674
9.30000	-0.202	-17.571	-27.897	-1.365	1.983	0.518	15.926
9.60000	-0.050	-32.058	-41.970	-8.240	24.927	1.690	32.729
9.90000	-0.092	-35.974	-45.475	-0.984	26.025	0.401	29.199
10.2000	-0.204	-27.523	-36.614	-0.783	6.245	0.322	20.258
10.5000	-0.735	-16.110	-24.789	-2.151	3.111	0.725	13.842
10.8000	-2.163	-11.020	-19.284	-5.956	4.632	1.210	12.684
11.1000	-0.775	-14.603	-22.443	-10.653	5.203	1.682	16.456
11.4000	-6.126	-1.927	-9.333	-13.882	1.362	1.173	7.886
11.7000	-0.586	-10.228	-17.182	-1.720	1.184	0.553	5.389
12.0000	-0.227	-16.072	-22.555	-1.546	1.254	0.570	9.208

For more information:
United States*
Europe*
Asia Pacific/Australia: (65) 290-6360
Canada: (416) 206-4725
Japan: (81 3) 3331-6111

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