Designing With The MSA-9970

Application Note S008

Introduction

The MSA-9970 differs from other products in the MSA Series in that designs with this device are expected to use external circuit elements to establish RF performance. Through proper selection of this external circuitry, a designer can use the MSA-9970 to build a variety of special purpose amplifiers. This Application Note shows how to use this Monolithic Microwave Integrated Circuit (MMIC) in three such designs.

Like other products in the MSA Series, the MSA-9970 is a Darlington feedback amplifier intended to function as an RF gain block. (A Darlington pair is used instead of a single transistor to increase the useful gain-bandwidth product of the resulting amplifier). An understanding of how feedback amplifiers work gives insight into some of the possible special uses of the MSA-9970. This note therefore starts with a brief review of resistive feedback amplifiers.

Resistive Feedback Primer[1]

Resistive Feedback and RF Performance

The fundamental concept underlying the design of resistive feedback amplifiers is that of constant gain-bandwidth product. Figure 1 shows a generic graph of open loop gain versus frequency for an amplifying device. The curve has a low frequency region over which gain is flat, a corner frequency at which gain starts to decrease, and a high frequency region over which gain is decreasing at a constant rate. The corner frequency is called f_β; the frequency at which the gain drops to unity (x 1 multiplication, or no gain) is called the transistion frequency, or f_t.

The open loop gain versus frequency curve shows the highest gain that can be achieved when building an amplifier with a selected amplifying device. This is another way of saying that the gain-versus-frequency curve for a resistive feedback amplifier must fit under the open loop gain-versus-frequency curve of the device with which it is built. It is therefore apparent that to increase the bandwidth of a resistive feedback amplifier, gain must be sacrificed – the only way to have a longer flat region in the amplifier gain-versus-frequency response is to have a

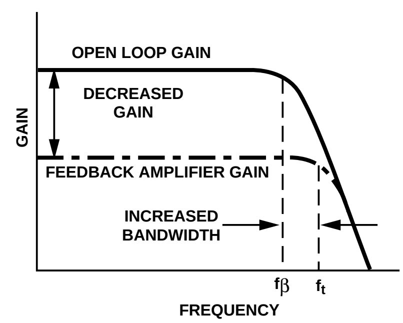

Figure 1. Feedback and Gain-Bandwidth Product

lower curve. Feedback is a convenient way of making this trade; using feedback for amplifier design can be thought of as the fine art of trading gain for bandwidth.

Feedback can be added in two different ways. SHUNT feedback elements connect the input of the device to the output. The amount of feedback presented by a shunt element is ***inversely proportional*** to its impedance: low impedances in shunt provide large amounts of feedback. SERIES feedback elements connect the common terminal of the device to ground. The amount of feedback presented by a series element is ***proportional*** to its impedance: high impedances in series provide large amounts of feedback. For a bipolar transistor in common emitter configuration, a shunt feedback resistor would connect the base and collector; a series feedback element would connect the emitter to ground.

In addition to altering the gain-bandwidth product of the amplifier, feedback also alters the impedance match. When only one feedback element is used, setting the impedance match will automatically set the gain (and therefore bandwidth) as well. If both series and shunt feedback elements are used, the designer has independent control of both gain and impedance match.

A few simple equations help quantify the effects of resistive feedback on common emitter bipolar transistor amplifiers. The bandwidth BW of an amplifier is a function of both the transconductance g_m and the transition frequency f_t of the transistor used, and of the load resistance R_L and the series feedback resistance R_E. It can be approximated from:

$$BW = \frac{(1 + g_m R_E)(f_t)}{g_m R_L}$$

The transconductance g_m of a bipolar transistor is bias dependent and can be calculated (at room temperature) from:

$$g_m = I_E\,(\text{mA}) / 26$$

where I_E (mA) is the transistor emitter current in milliamperes. The feedback amplifier built with this transistor will have a modified transconductance g'_m given by:

$$g'_m = g_m / (1 + g_m R_E).$$

The low frequency gain of the feedback amplifier is a function of g'_m and the system characteristic impedance Z_O, and can be approximated from [2] :

$$S_{21} = -(g'_m Z_O - 1).$$

There is also a relationship between the shunt feedback resistor RF, the amplifier transconductance g'_m and the system characteristic impedance Z_O:

$$R_F = g'_m Z_O^2$$

Note that for the case $g_m R_E >> 1$ this equation reduces to:

$$R_F R_E = Z_O^2$$

By examining these equations, it can be seen that R_E can be chosen to set amplifier bandwidth – and therefore amplifier transconductance and gain, and that R_F can be chosen to set amplifier match.

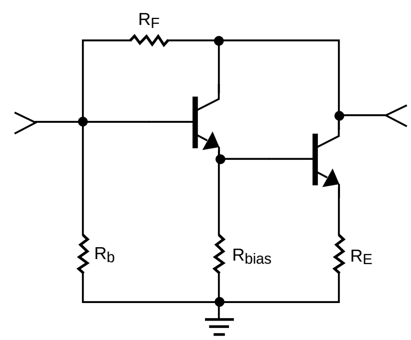

Figure 2a. Conventional MSA Series

Resistive Feedback And DC Performance

When resistors are used as feedback elements, they alter not only the RF performance of the transistor, they change the DC bias point as well. Most MSA Series (MSA-01, 02, 03, 04, 06, 07, 08) make use of this fact, using the feedback resistors and a resistor “R_B” from the base of the input transistor to ground to set up a divider network that biases both transistors of the Darlington (see Figure 2a).

This simple way of biasing is not viable when it results in large amounts of power being dissipated in the feedback resistor. Either low values of R_F (large amounts of feedback) or large output to input voltage drops across the Darlington pair can cause this to occur. Power dissipated in R_F not only has the potential of causing the feedback resistor to fail, it also heats the MMIC and raises the junction temperature of the active devices, accelerating electro-migration and reducing expected lifetime.

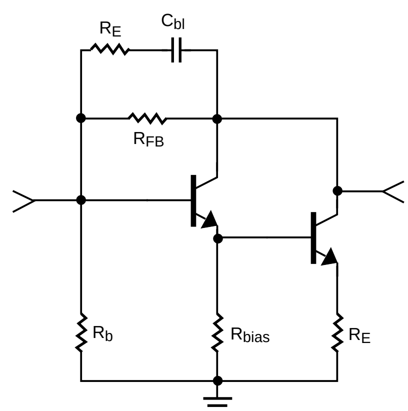

Figure 2b. MSA Series with DC Blocked Shunt Feedback

A solution to this problem is to place a DC blocking capacitor in series with R_F and provide an alternate, high resistance path from input to output that will set the bias but not effect the RF feedback (see Figure 2b). The drawback to this solution is that at some low enough frequency, this blocking capacitor will become an RF open circuit, rendering the shunt feedback inoperative. The result is that MSA Series which use this bias scheme (MSA-05, 09, 10 and 11) will have a lower limit to the frequency of operation, below which the match worsens and the gain increases towards the open loop gain of the Darlington.

Applications

Application 0: MSA-0910 Versus MSA-9970

The MMIC die from which the MSA-9970 is made is the variety that requires the use of a blocking capacitor in series with the shunt feedback resistor. When this die is packaged conventionally, the on-chip shunt feedback resistor is bonded to an off-chip (but in-package) blocking capacitor to form the shunt feedback loop. The value of the blocking capacitor used is 45 pF, the largest value that will fit in the 100 mil square stripline package. The resulting MSA Series has 8.0 ± 0.2 dB gain typical from 100 MHz to 4.0 GHz, and is sold under the part number MSA-0910.

In contrast, when the die is packaged as an MSA-9970 the on-chip shunt feedback resistor is left unconnected, and is not accessible from the package pin outs. Since the MSA-9970 does not use an in-package blocking capacitor, the smaller 70 mil square stripline package can be used. The result is an open loop gain block with built-in series feedback, but with no shunt feedback elements. With the selection of the shunt feedback loop entirely in the control of the designer, a number of special purpose circuits can now be realized. If the specifications of the MSA-0910 meet the requirements of a design, there is no reason to do the extra circuit work required to make the MSA-9970 fulfill the application. There are, however, numerous special cases where improved performance can be achieved by providing specially selected external shunt feedback to the MSA-9970.

Application 1: Extended Low Frequency Performance

An obvious application for the MSA-9970 is to build an MSA Series circuit that has good match and gain flatness and that operates to lower frequencies than does the MSA-0910. The external feedback used to achieve this performance consists of a resistor in series with a blocking capacitor, connected in shunt with the device. The value of this blocking capacitor will determine how low in frequency the feedback is operative, and thus set the lower frequency of operation of the design. Since the blocking capacitor is external to the package, very large values can be used (e.g. > 1 μF), essentially resulting in arbitrarily low frequencies of operation.

The high frequency of operation will be determined by the parasitic inductance in the feedback paths. Grounding must be excellent, or unwanted inductance will act as additional series feedback and cause significant gain rolloff at high frequencies. It is interesting to note, however, that in some circuits a designed-in amount of inductance in the form of a short transmission line in the common lead path will improve high frequency performance, and yield an amplifier with superior gain flatness.

A critical aspect of this design is that parasitic inductances in the shunt feedback path will create high frequency resonances that result in significant gain ripple. These effects, most common above 2.0 GHz, are very dependent on the physical structure (as opposed to the electrical value) of the feedback components. It is difficult to predict these effects accurately with computer simulations, as sufficiently detailed models of the parasitics associated with the shunt feedback are rarely available. The most reliable technique for achieving the best bandwidth is to construct the feedback from quality low parasitic chip components, and connect the device input to output via the shortest possible path. Often “piggy-backing” feedback components over the top of the MSA-9970 will yield the best performance. An alternative technique requires the use of a transmission line long enough to route the shunt feedback around one of the ground leads of the MSA-9970. In this kind of layout tolerances on all feedback components must be tightly controlled to keep high frequency resonances from occurring in the pass band of the amplifier.

The schematic for an extended low frequency amplifier using the MSA-9970 is shown in Figure 3. This amplifier uses an R_F of 270 Ω in the shunt feedback path, and a small transmission line in the series feedback path. A 250 mil long transmission line routes the shunt feedback around the ground leads of the MSA-9970. Input, output, and feedback blocking capacitors are all 1000 pF, a value large enough to give good low frequency performance. The 1 nH inductor shown in the shunt feedback path is the sum of the parasitic inductances associated with the chip resistor and the chip capacitor, not a separate physical element.

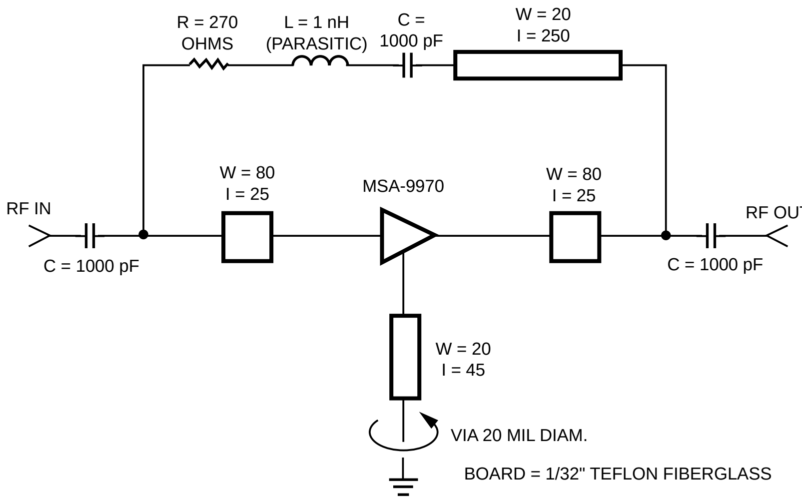

Figure 3. MSA-9970 Extended Low Frequency Amplifier

This amplifier has 10.9 ± 0.2 dB gain from 20 MHz to 3.5 GHz, with 13 dB typical input return loss and 17 dB typical output return loss. The good match insures the amplifier is easily cascadable. The design is unconditionally stable at all frequencies below 3.0 GHz. Above 3.0 GHz care will have to be taken to insure the terminating impedances presented are in the stable region of the amplifier.

Performance curves showing gain and match versus frequency are shown in Figure 4. Performance is shown in tabular form in Table 1. A TOUCHSTONE simulation of the amplifier is given in Table 2.

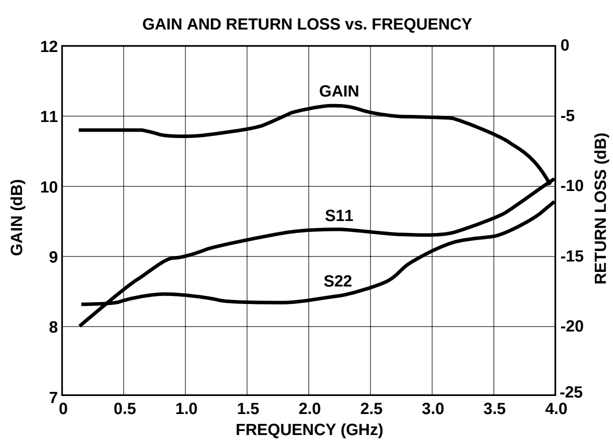

Figure 4. MSA-9970 Extended Low Frequency Amplifier

Table 1. MSA-9970 Extended Low Frequency Ampifier

Freq (GHz)	Gain (dB)	S_{11} (dB)	S_{22} (dB)	k
0.02	10.9	-20.7	-19.0	1.11
0.05	10.8	-20.0	-19.2	1.11
0.10	10.8	-19.7	-18.6	1.11
0.20	10.8	-19.7	-18.6	1.11
0.40	10.8	-18.5	-18.5	1.11
0.60	10.8	-17.3	-17.8	1.10
0.80	10.7	-15.9	-17.7	1.09
1.00	10.7	-15.4	-17.7	1.08
1.50	10.8	-13.9	-18.5	1.05
2.00	11.1	-13.3	-18.3	1.03
2.50	11.0	-13.4	-17.5	1.02
3.00	11.0	-13.7	-14.8	0.99
3.50	10.7	-12.4	-13.6	0.94
4.00	10.0	-9.4	-11.5	0.84
4.50	8.6	-6.7	-9.5	0.69
5.00	6.6	-4.6	-7.6	0.49
5.50	4.1	-3.2	-6.3	0.31
6.00	1.1	-2.5	-5.9	0.24
6.50	-2.1	-2.1	-6.2	0.26
7.00	-5.4	-1.9	-7.1	0.40

Table 2. MSA-9970 Extended Low Frequency Amplifier

```
CKT
        MSUB    ER=2.5   H=32    T=1       RHO=1       RGH=0

        SLC     1        2       L=.5      C=1E6
        SRLC    2        51      R=270     L=1         C=1E6
        MLIN    51       5       W=20      L=250
        MLIN    2        3       W=80      L=25
        S2PA    3        4       41        A9970I35.S2P
        MLIN    41       42      W=20      L=45
        VIA     42       0       D1=20  D2=20  H=32  T=1
        MLIN    4        5       W=80      L=25
        SLC     5        6       L=.5      C=1E6
        DEF2P   1        6       AMP
FREQ
        STEP    .02      .05     .1
        SWEEP   .2       1.0     .2
        SWEEP   1.5      7.0     .5

OUT
        AMP     DB [S21]
        AMP     DB [S11]
        AMP     DB [S22]
        AMP     K
```

Application 2: 75 Ohm, Minimum VSWR Amplifier

Since the impedance match of an amplifier can be set by the feedback, designs using the MSA-9970 are not limited to systems with 50 ohm characteristic impedance. Appropriate selection of the shunt feedback resistor value will result in an amplifier that is well matched for any specific impedance system.

In addition, the impedance match achieved with the MSA-9970 can be almost arbitrarily good provided the design bandwidth is not too extreme. This is as true in a 50 ohm system as it is in a system of any other characteristic impedance.

The amplifier depicted schematically in Figure 5 makes use of both of these observations. This amplifier has useful gain across the entire television frequency range (50 MHz to 900 MHz), and is designed to operate into the 75 Ω characteristic impedance used in the television industry. A point of particular interest is the excellence of the impedance match. Both input and output return losses are greater than 20 dB from 20 MHz to above 1.0 GHz. This superior VSWR performance comes about because the impedance match has been “hand tailored” for the desired frequency range through proper selection of the value of R_F.

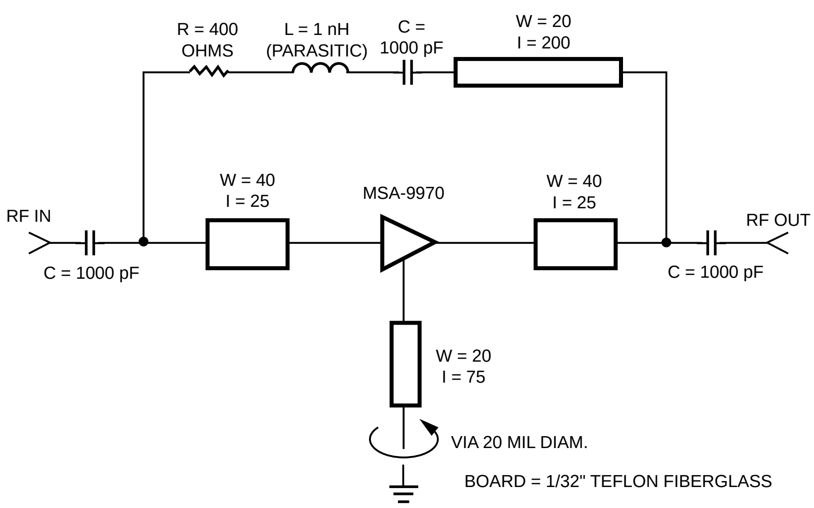

Figure 5. MSA-9970 75 Ohm, Minimum VSWR Amplifier

The topology of the schematic is identical to that used for the extended low frequency performance amplifier of Example 1. The feedback resistor R_F now has a value of 400 Ω, and slightly more series feedback (i.e. a longer transmission line in the emitter return) is used. The R_F input and output transmission lines have a characteristic impedance of 75 Ω instead of 50 Ω.

Performance curves showing gain and match versus frequency are shown in Figure 6. Performance is listed in tabular form in Table 3. Note that the amplifier is unconditionally stable throughout its operating range. The TOUCHSTONE file for the amplifier simulation is given in Table 4.

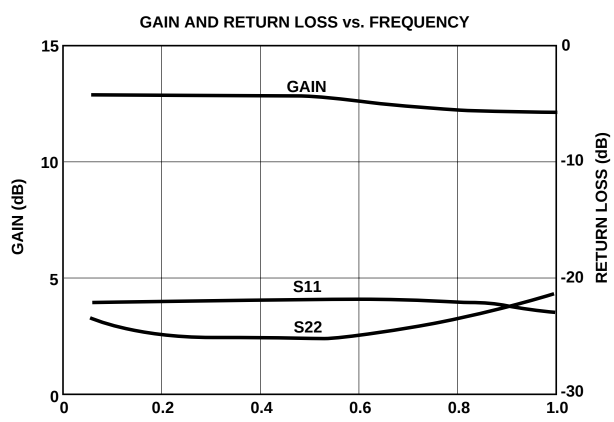

Figure 6. MSA-9970 75 Ohm, Minimum VSWR Amplifier

Table 3. MSA-9970 75 Ohm, Minimum VSWR Ampilfier

Freq (GHz)	Gain (dB)	S_{11} (dB)	S_{22} (dB)	k
0.02	12.9	-21.1	-23.9	1.08
0.05	12.9	-21.9	-23.4	1.08
0.10	12.9	-21.9	-24.3	1.07
0.20	12.8	-21.6	-25.0	1.08
0.30	12.8	-21.5	-25.0	1.08
0.40	12.7	-21.5	-25.0	1.08
0.50	12.6	-21.7	-25.2	1.08
0.60	12.5	-21.9	-25.0	1.08
0.70	12.3	-21.9	-24.4	1.08
0.80	12.2	-21.9	-23.7	1.08
0.90	12.0	-22.4	-22.4	1.08
1.00	11.9	-22.9	-21.3	1.08

Table 4. MSA-9970 75 Ohm, Minimum VSWR Amplifier

```
CKT
        MSUB     ER=2.5    H=32      T=1       RHO=1       RGH=0

        SLC      1         2         L=.5      C=1E6
        SRLC     2         51        R=400     L=1         C=1E6
        MLIN     51        5         W=20      L=200
        MLIN     2         3         W=40      L=25
        S2PA     3         4         41        A9970I35.S2P
        MLIN     41        42        W=20      L=75
        VIA      42        0         D1=20   D2=20   H=32   T=1
        MLIN     4         5         W=40      L=25
        SLC      5         6         L=.5      C=1E6
        DEF2P    1         6         AMP

TERM
        AMP      .2        0                   .2          0

FREQ
        STEP     .02       .05
        SWEEP    .1        1.0       .1

OUT
        AMP      DB [S21]
        AMP      DB [S11]
        AMP      DB [S22]
        AMP      K
```

Application 3 : Opposite Gain Slope Amplifier

One of the most common problems a microwave circuit designer faces is high frequency gain rolloff. Each amplifier stage tends to have slightly less gain at the high band end than at lower frequencies. A cascade of many such stages, all with the same gain versus frequency characteristic, ends up with a drastic decrease in gain at the high band end. An interesting solution to this problem is to include in the cascade an amplifier whose gain actually ***increases*** with frequency. Such an amplifier, sometimes called an "opposite gain slope amplifier" because it exhibits the opposite gain slope of a "normal" amplifier, can be easily constructed from the MSA-9970.

This design is accomplished by providing "too much" feedback in the shunt path. (In more rigorous technical terms, it is accomplished through the introduction of a zero to cancel one of the poles of the amplifier transfer function. This kind of design is consequently also known as "pole-zero compensation".[3]) At low frequencies, the value of R_F establishes the gain. At higher frequencies, the unavoidable inductances in the feedback path increase its effective impedance, providing less feedback and hence more gain. Careful tailoring of R_F and the amount of inductance in the feedback path will allow the designer to select the amount of gain slope the final amplifier has.

The schematic for an opposite gain slope amplifier is shown in Figure 7. Note that this amplifier has a lower valued feedback resistor (more shunt feedback) than either of the two preceeding examples. This design also does not use any additional reactive series feedback – there is no transmission line in the ground return path.

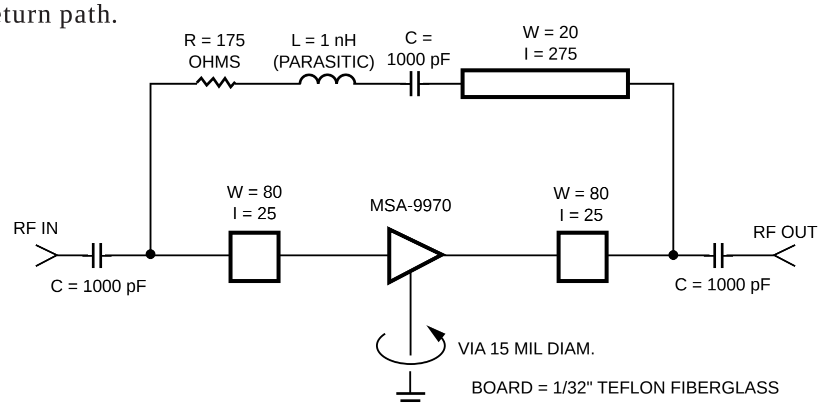

Figure 7. MSA-9970 Opposite Gain Slope Amplifier

Amplifier performance is shown in Figure 8. The data is repeated in tabular form in Table 5. The TOUCHSTONE circuit file is given in Table 6. Note that the gain increases from 8.5 dB at 50 MHz to 14 dB at 2.4 GHz. The amplifier is also well matched, and therefore readily cascadable. Both input and output return loss are typically on the order of 20 dB across the design range, with a worst case match of 15.7 dB. Stability is also good, with only a negligibly small potentially unstable region appearing near 2.0 GHz.

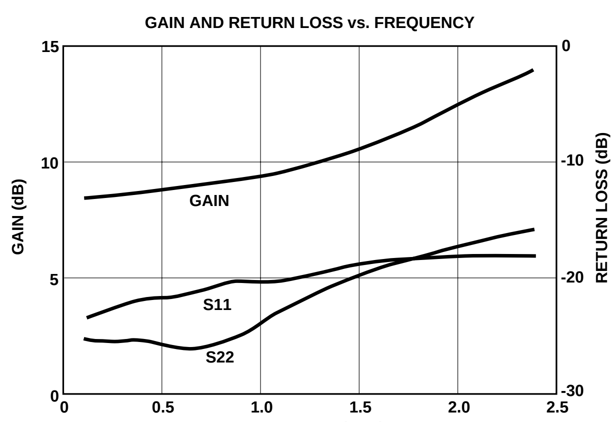

Figure 8. MSA-9970 Opposite Gain Slope Amplifier

Table 5. MSA-9970 Opposite Gain Slope Amplifier

Freq (GHz)	Gain (dB)	S_{11} (dB)	S_{22} (dB)	k
0.02	8.5	-22.8	-24.8	1.17
0.05	8.5	-23.5	-24.5	1.17
0.10	8.5	-23.7	-25.5	1.16
0.20	8.5	-22.9	-25.5	1.17
0.40	8.6	-22.0	-25.3	1.16
0.60	8.8	-21.7	-26.2	1.14
0.80	9.0	-20.6	-25.6	1.12
1.00	9.3	-20.5	-23.7	1.09
1.20	9.7	-19.9	-21.9	1.07
1.40	10.3	-19.3	-20.3	1.05
1.60	10.9	-18.9	-19.1	1.02
1.80	11.7	-18.5	-18.2	1.00
2.00	12.6	-18.4	-17.2	0.99
2.20	13.3	-18.1	-16.5	0.99
2.40	14.0	-18.0	-15.7	1.00

Table 6. MSA-9970 Opposite Gain Slope Amplifier

```
CKT
        MSUB     ER=2.5   H=32    T=1      RHO=1    RGH=0

        SLC      1        2       L=.5     C=1E6
        SRLC     2        51      R=175    L=1      C=1E6
        MLIN     51       5       W=20     L=275
        MLIN     2        3       W=80     L=25
        S2PA     3        4       41       A9970I35.S2P
        VIA      41       0       D1=15  D2=15  H=32  T=1
        MLIN     4        5       W=80     L=25
        SLC      5        6       L=.5     C=1E6
        DEF2P    1        6       AMP

FREQ
        STEP     .02      .05     .1
        SWEEP    .2       2.4     .2

OUT
        AMP      DB [S21]
        AMP      DB [S11]
        AMP      DB [S22]
        AMP      K
```

Conclusions

This Application Note has presented the MSA-9970, an MMIC gain block with user selectable feedback. Several simple designs have been given, resulting in amplifiers with extended low frequency performance, operation into alternate impedance systems, superior match, and opposite gain slope.

The potential of this device is not limited to these applications. Other possibilities included AGC amplifiers (e.g. by using a FET as a voltage variable R_F), amplifiers with gain versus temperature compensation (e.g. by using a thermistor or sensistor as a temperature variable feedback element), and variable frequency oscillators (e.g. by providing a varactor controlled feedback loop with the oscillator). It is left to the designer to investigate these and other possibilities.

References

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2. K. Niclas et. al., “The Matched Feedback Amp”, *MTT*, 1980, pp. 285-294.

3. B. Kuo, *Automatic Control Systems*, 1982, pp. 507-517.

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