CEL California Eastern Laboratories

APPLICATION NOTE

AN1020
Active Mixer Design Using the NE25139 Dual Gate MESFET

Introduction

This application note documents the design method and results of using the NE25139 as an active mixer for the ISM band of 902-928 MHz. The IF frequency will be 70 MHz, and the LO frequency range will be 832-858 MHz. The design goals for this mixer are to have a conversion gain of at least 11 dB, and a noise figure lower than 7 dB while keeping the costs as low as possible. The NE25139 could be used as a mixer in ISM band spread spectrum radios, cellular telephones, or any UHF applications.

Design Philosophy and Method

The challenge to every receiver designer is to have a front end that is sensitive and at the same time robust in a multiple signal environment. Excessive gain before the IF filtering can make the receiver sensitive, but at the same time very vulnerable to saturation and intermodulation by unwanted signals. The trick is to have adequate gain to set the noise figure but not excessive gain.

Active mixers have some advantages over passive double balanced mixers. The most obvious advantage is that they provide gain instead of loss. This reduces the gain requirements on the low noise amplifier and the IF stage in a receiver. **Figure 1** shows some possible receiver line ups that illustrate the advantages to having conversion gain (active mixer) as opposed to conversion loss (passive mixer). The first line up has a composite noise figure of 4.45 dB and uses an active mixer with the design goals of this application note. The second line up uses a typical double balanced mixer and has a composite noise figure of 4.46 dB. Note that two stages of amplification will be required to achieve 27 dB of gain in the preamp. Also, a typical double balanced mixer requires at least +7 dBm of LO drive power. It will be shown later that only +3 dBm of LO power will be required for the active mixer. The third line up has a composite noise figure of 5.31 dB and uses an identical preamp as the first line up. Note that an extra gain stage in the IF is necessary to keep the noise figure from becoming too excessive. It will also be shown later that an active mixer designed with the NE25139 can cost much less than a typical double balanced mixer.
In a dual gate FET mixer, down conversion is achieved by

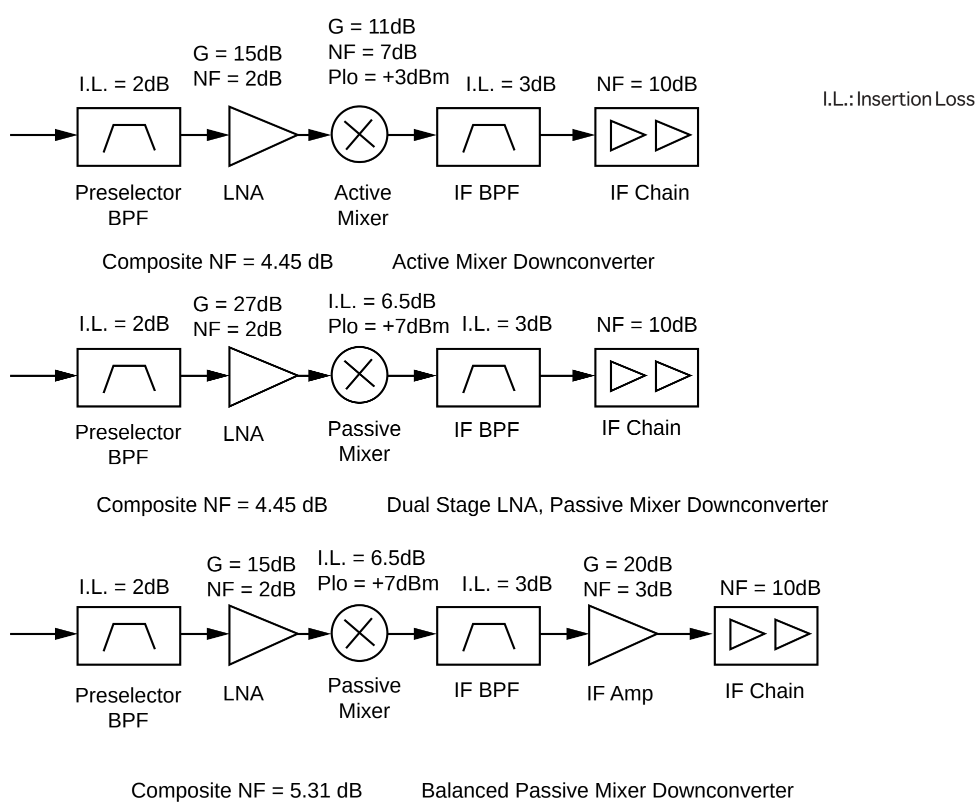

Figure 1. Different downconverter topologies.

varying the transconductance with a local oscillator signal on one gate and applying the RF signal to the other gate. The IF signal is then extracted from the drain.

Designing a mixer with the NE25139 boils down to an impedance matching problem. The RF gate should be conjugately matched at the RF frequency and see a short circuit at the IF frequency. The LO gate should be conjugately matched at the LO frequency and short circuited at the IF frequency. Shorting the gates at the IF frequency helps prevent amplification of noise that would fall into the IF passband, and hence, helps to lower the noise figure of the mixer. Shorting the gates at the IF frequency also increases the conversion gain. The drain should be conjugately matched at the IF frequency and short circuited at the RF and LO frequencies. According to Maas[1] short circuiting the drain at the RF and LO frequencies provides a stable termination over a broad range of frequencies and provides for optimum gain and noise figure at the IF frequency. Another important advantage is that it helps attenuate LO feed through into the IF output.

Impedance Matching the NE25139

Although a mixer is a nonlinear circuit the linear S-parameters can be used as a starting point for the impedance matching task. Then with some intelligent, empirical optimization on the lab bench, the job can be finished. The S-parameters at the IF, RF, and LO frequencies are shown in **Table 1**. (VDS = 5 V, IDS = 10 mA, VGS 2 = 1V). Even though these are not the exact bias conditions that will be used, these S-parameters will be close enough. The bias conditions that will be used in the actual design are VDS = 4.2V, IDS = 7.5 mA, VGS1 = VGS2 =-0.75 V.

S-Parameter	70 MHz(IF)	845 MHz(LO)	915 MHz(RF)
S_{11}	0.99 < -3°	0.95 < -25°	0.94 < -29°
S_{21}	2.36 < 177°	2.23 < 142°	2.45 < 137°
S_{12}	0.001 < 87°	0.005 < 79°	0.005 < 79°
S_{22}	0.97 < -1°	0.96 < -9°	0.99 < -13°

Table 1. Linear S-parameters

The impedance at each port of the mixer can be calculated using the formulas from Gonzalez[2]

$$\Gamma_o = S_{22} + (S_{12}S_{21}\Gamma_s) / (1 - S_{11}\Gamma_s)$$

and

$$\Gamma_i = S_{11} + (S_{12}S_{21}\Gamma_L) / (1 - S_{22}\Gamma_L)$$

where Γ_i is the input reflection coefficient, Γ_L is the load reflection coefficient, Γ_o is the output reflection coefficient, and Γ_S is the source reflection coefficient. Some assumptions must be made in order to make these calculations. These assumptions are as follows: the drain is short circuited at the RF and LO frequencies; the gates are well isolated from one another, and the gates are short circuited at the IF frequency. The reason for the good isolation between the gates is that the gate to gate capacitance is very low. Even though the S-parameters were measured with the transistor configured as a two port device, assuming that the impedance is equal at both of the gates is still a reasonable approximation. The main goal of the impedance matching calculations is to come up with a good topology that will be close and that can be optimized on the bench. Because the drain is short circuited at the RF and LO frequencies Γ_L =-1 is used in the formulas for the RF and LO reflection coefficient calculations. Because the gates are short circuited at the IF frequency Γ_S =-1 is used for the IF reflection coefficient calculations. Plugging the S-parameters and the source and load reflection coefficients into the formula gives

$$\Gamma_{RF} = 0.93 < -28.3°$$
$$\Gamma_{LO} = 0.95 < -24.7°$$
$$\Gamma_{IF} = 0.97 < -0.9°$$

Now the formula from Gonzales[2]

$$Z = Z_o [(1 + \Gamma) / (1 - \Gamma)]$$

where Z_o = 50 Ω, can be used to convert the reflection coefficients into impedances. The results of these calculations are shown below:

$$Z_{RF} = 29.7 - j194\ \Omega$$
$$Z_{LO} = 26.5 - j225.4\ \Omega$$
$$Z_{IF} = 2{,}472 - j1{,}416\ \Omega$$

where Z_{RF} is the impedance looking into gate 2 at the RF frequency, Z_{LO} is the impedance looking onto gate 1 at the LO frequency, and Z_{IF} is the impedance looking into the drain at the IF frequency.

The impedance matching topology and biasing circuitry are shown in **Figure 2**. Note that the source is bypassed at RF frequencies with the 47 pF capacitor and at IF frequencies with the 0.01 uF capacitor. This is critical for maintaining stability.

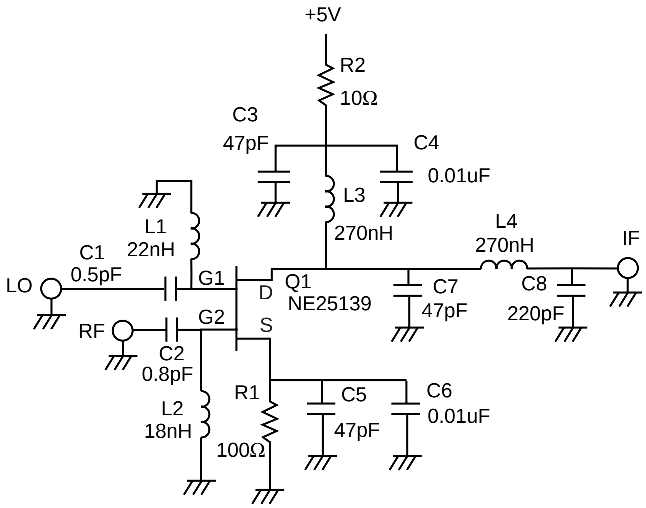

Figure 2. Calculated Value Based on Small Signal S-parameters.

It is best to have the source well bypassed for the broadest range of frequencies possible. The gates are matched to 50 ohms with a shunt inductor and series capacitor. Note that the shunt inductor will provide the desired short circuit at the IF frequency. The inductors at the gates also provide a DC ground to bias the transistor. R1 in the source sets the drain current to about 7.5 mA. R2 helps to isolate the mixer circuit from the power supply and very little voltage is dropped across it. The drain is matched to 50 ohms with a π circuit. Using a π topology lowers the Q of the matching and also serves as a low pass filter to attenuate LO feed through. C7 provides the short circuit at the LO and RF frequencies.

Now that the initial calculations have been completed, the circuit must be optimized on the lab bench. The input impedance on both of the gates is somewhat dependent on the amount of LO power used. If the FET is biased at IDS = 7.5 mA, about +3 dBm of LO power is a good place to start. Using a network analyzer you can quickly see how close the impedance match is by monitoring the return loss at each of the ports. A deep notch in the return loss should occur at the center frequency for each of the ports. When matching the RF and IF ports, be sure to have +3 dBm of LO power pumping the LO gate. Also, be sure the network analyzer output power is low enough to ensure small signal measurements at the RF and IF ports, and that the output power of the network analyzer is set close to +3 dBm when measuring the return loss at the LO port. Although the ports are well isolated from each other, the LO drive affects the biasing and hence the impedance at all the ports. While adjusting the impedance matching values at each port watch the effect each change has on the return loss notch. In this manner, the notch can be moved to center frequency and a good match will be achieved. If a network analyzer is not available, a tracking generator, spectrum analyzer, and a directional coupler can be used to monitor the return loss as the elements are adjusted. It is highly recommended that this circuit be optimized by first making sure that all the ports are well matched. Simply adjusting element values while monitoring the gain can be a frustrating and time consuming experience. Fortunately, all the ports are well isolated from one another and can be independently matched one at a time. As soon as the ports are matched the gain will be achieved. Conjugately matching all the ports gives the best noise figure and gain. **Figure 3** shows the final mixer circuit that has been empirically optimized. When first measured the return loss notch at the LO gate was 100 MHz too high and the return loss notch at the RF gate was 150 MHz too low. The return loss switch at the IF port was 40 Mhz too low. Air wound coils were used for L1 and L2. Optimization of the matching at the gates was easily accomplished by knifing apart the windings or squeezing them together. Simply lowering the value of C8 matched the impedance at the IF port. It was found that the best noise figure was achieved with IDS = 3.5 mA. At 915 MHz the SSB noise figure was 5.4 dB and the gain was 11.7 dB. The conversion gain return loss and noise figure at the RF port are graphed in **Figure 4**. The return loss at the IF port was 22 dB. With P_{LO} = +3 dBm, the P1dB was measured to be -1 dBm, and the $IP3_{OUT}$ was measured to be +7.5 dBm. The LO to RF isolation is 21 dB and the LO to IF isolation is 31 dB.

If an even higher P1dB and IP3 are desired, it can be achieved by optimizing the circuit for best P1dB and IP3. A much higher IP3 can be achieved by increasing the drain current; however, an increase in noise figure will result.

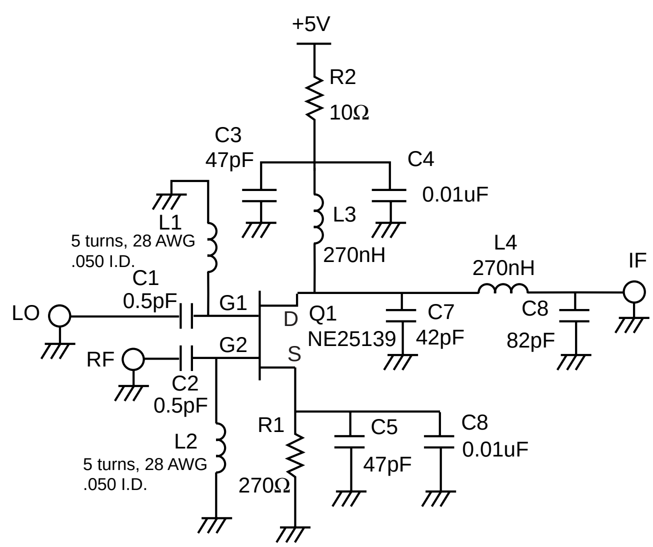

Figure 3. Optimized Value for Best Noise Figure.

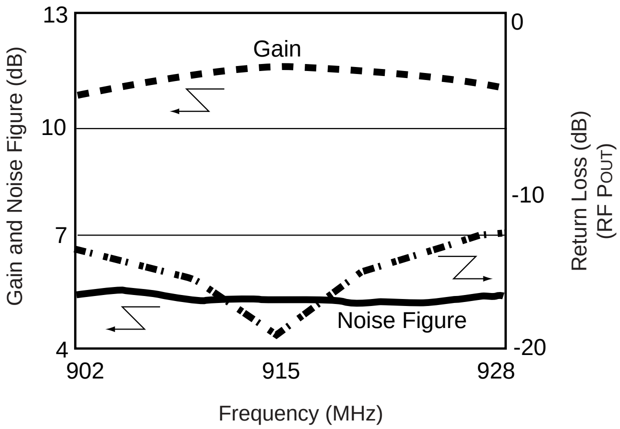

Figure 4. Mixer with Best Noise Figure

A second mixer circuit was optimized on the bench for best P1dB and IP3. The bias point was changed to the original 7.5 mA. The matching elements on the gates were empirically modified while monitoring the P1dB and IP3 performance. **Figure 5** shows the optimized values for the higher linearity mixer. With P_{LO} = +3 dBm, the P1dB was measured to be +4 dBm, and the $IP3_{OUT}$ was measured to be +15 dBm. At 915 MHz the SSB noise figure was 11 dB and the gain was 10.7 dB. The conversion gain, the return loss and the noise figure are graphed in **Figure 6**. The return loss at the IF port was 24 dB. The LO to RF isolation is 46 dB and the LO to IF isolation is 16 dB and the LO to IF isolation is 24 dB.

The input and ouput impedances of the NE25139 are very high. This makes the matching a little bit touchy and narrow band. In narrow band receivers (e.g., the RF bandwidth is less than 50 MHz) this can be advantageous. Both of the circuits

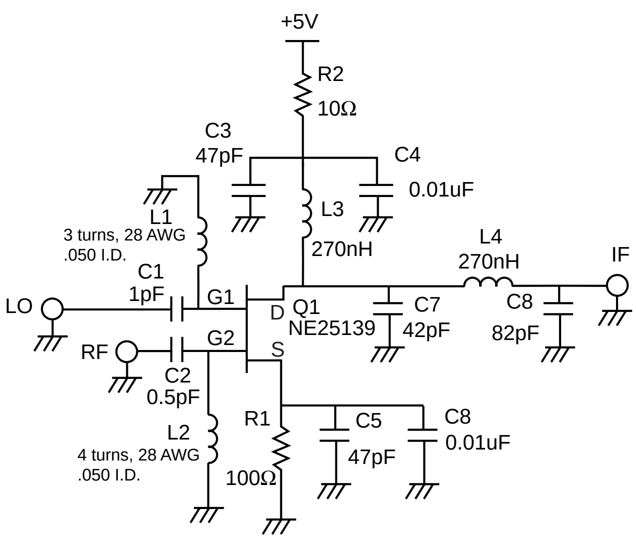

Figure 5. Optimized Value for Best Linearity

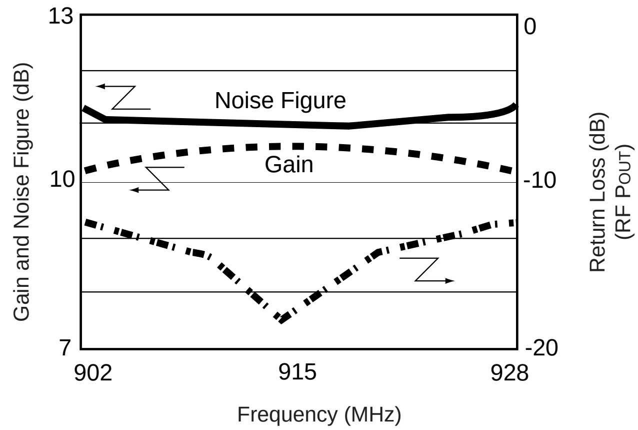

Figure 6. Mixer with Best Linearity

in **Figures 3 and 5** had -5 dB of conversion gain at the image frequency. This provides 16.7 dB of image rejection for the circuit in **Figure 3** and 15.7 dB of image rejection for the circuit in **Figure 5**. The image rejection performance of a receiver could be improved by as much as 16.7 dB without adding any cost to the preselector filter. Or the requirements on the preselector filter could be relaxed to provide further cost saving. To ensure consistent performance yield in production, the air wound coils should be adjusted while monitoring the gain somewhere in the IF stage with an oscilloscope.

The local oscillator power was varied +/- 3 dB on both versions of the mixer and the effects this had on conversion gain and noise figure are shown in **Tables 2 and 3** below.

P_{LO}	Gain	NF
0 dBm	11.6 dB	5.9 dB
3 dBm	11.7 dB	5.4 dB
6 dBm	11.8 dB	5.0 dB

Table 2. Best Noise Figure Circuit

P_{LO}	Gain	NF
0 dBm	10.5 dB	12 dB
3 dBm	10.7 dB	11 dB
6 dBm	10.9 dB	10.5 dB

Table 3. Best Linearity Circuit

As can be seen the mixer performance was not critically affected by small changes in the LO power. This should make the variations in LO power that can occur in production non-critical.

The NE25139 is available in several IDSS ranges. The U73 range was used for this circuit (IDSS = 20 - 30 mA). The higher IDSS range devices will give better third order intercept point performance. If the U74 range were to be used even better third order intercept point performance can be expected. It is highly recommended that at least the U73 range device be used when designing a mixer.

Table 4 shows the parts list for the circuit in **Figure 3** (best noise figure circuit) and the cost of the parts in 100K quantities.

Reference Designator	Description	Cost*
Q1	NE25139T1U73 Dual Gate MESFET	0.76
C1, C2	0.5 PF, NPO CAP, 0805, +/- 0.1PF	0.045
C4, C6	0.01 UF, CAP, 0805, +/- 10%	0.015
C3, C5	47 PF, NPO CAP, 0805, +/- 5%	0.015
C7	42 PF, NPO CAP, 0805, +/- 5%	0.015
C8	82 PF, NPO CAP, 0805, +/- 5%	0.015
R2	10 Ohm, Resistor, 0805, +/- 10%	0.005
R1	270 Ohm, Resistor, 0805, +/- 10%	0.005
L1, L2	270 NH, Inductor, 0805, +/- 10%	0.13
L3, L4	Air Wound Coil, 5 turns, 26 AWG, 0.050 Inch Inner Diameter	0.05
Total Cost of Mixer in 100K Quantities		1.31

Table 4. Best Noise Figure Circuit Parts List

* *The cost reflected in this table is an estimate based on information available as of the date of publication. For the latest prices, contact California Eastern Laboratories.*

The total parts cost for 100K quantities in production is only $1.31 for the mixer circuit. Using the NE25139 as an active mixer relaxes the gain requirements in the LNA and the IF stage to achieve a given receiver sensitivity. The requirements on the preselector filter to achieve a given image rejection can also be relaxed. These two advantages should result in further cost savings.

Conclusion

This application note presents the results of using NE25139 as an active mixer. It has been shown that simple impedance matching methods and empirical optimization can be used to design a high performance active mixer. A mixer that only uses 3.5 mA of current and +3 dBm of LO power was designed. The noise figure was 5.4 dB and the conversion gain was 11.7 dB. The output third order intercept point was +7.5 dBm. Because this mixer only uses 3.5 mA of current it would be ideal for battery operated receivers. Further current savings can also be obtained when using the NE25139 as an active mixer because fewer gain stages in the LNA or IF are required. It was also shown that higher IP3 performance could be achieved by increasing the drain current but a trade off in increased noise figure would result. By using the NE25139 as a discrete active mixer, the designer can optimize its performance to suit the application. There are many other topologies that could be used with the NE25139 to accomplish the impedance matching, providing the proper short circuits and conjugate matches are achieved. Cost savings and some performance advantages can be achieved by using the NE25139 instead of the standard passive double balanced mixers that are used in many designs.

References

1. Maas, S., Microwave Mixers, 2nd Ed. Artech House, 1993, pg. 315
2. Gonzalez, G., Microwave Transistor Amplifiers, Prentice-Hall, 1984, pg. 6 & 85.

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