
The Schottky Diode Mixer

Application Note 995

Introduction

A major application of the Schottky diode is the production of the difference frequency when two frequencies are combined or mixed in the diode. This mixing action is the result of the non-linear relationship between current and voltage, usually expressed as:

$$I = I_S \left(e^{\frac{q(V - IR_S)}{nkT}} - 1 \right)$$

The series resistance, R_S , is a parasitic element representing bulk resistance of the semiconductor and contact resistance. It is sometimes confused with dynamic resistance which is the sum of the series resistance and the resistance of the junction where the frequency conversion takes place.

The ideality factor, n , is unity for an ideal diode and less than 1.1 for a silicon Schottky diode.

Variations in n are not important for n less than 1.1 [1] and will not be considered in this note. The effect of saturation current, I_S , is very important when the level of local oscillator power is low. This will be demonstrated by comparing results of mixing with diodes having different values of saturation current. Although temperature, T , is seen in the exponential and is present in a more complicated manner in saturation current, the effect on mixing efficiency is less than 0.5 dB for 100°C change in temperature. Temperature effects are more serious in detector applications and are discussed in Application Note 956-6, *Temperature Dependence of Schottky Detector Voltage Sensitivity*.

Electron charge, q , and Boltzmann constant, k , may be combined in the equation:

$$I = I_S \left(e^{\frac{V - IR_S}{0.026}} - 1 \right)$$

Conversion Loss

Mixing efficiency is measured by the conversion loss, the ratio of signal input power to intermediate frequency output power. The intermediate frequency is the difference between the signal frequency and the local oscillator frequency. The diode may also generate the sum of these two frequencies. In this case the mixer may be called an upconverter. For a given local oscillator frequency, the difference frequency may be produced by two signal frequencies – one above the L.O. frequency and one below. Of course, noise is also contributed at these two frequencies. In some cases, the mixer is designed to respond to both these frequencies. A mixer of this type is called a double sideband mixer. More commonly the mixer is designed to respond to one of these inputs. Since noise comes from both frequencies the double sideband mixer is better – typically 3 dB better.

Noise figure is another measure of mixing efficiency. This is the ratio of signal to noise ratio at the input to signal to noise ratio at the output. Single and double sideband definitions apply to noise figure also. In some applications noise figure and conversion loss are essentially equal. However, noise figure includes diode noise which becomes significant at intermediate frequencies in the audio range (1/f noise). In these applications noise figure may be much larger than conversion loss.

Another complication of noise figure is the effect of the amplifier following the mixer. Diode manufacturers include the effect of a 1.5 dB noise figure I.F. amplifier in the mixer noise figure. Mixer manufacturers do not include this amplifier in the mixer noise definition. In this paper diode efficiency will be measured by conversion loss.

Parasitic Losses

The diode equivalent circuit of Figure 1 shows the presence of two elements that degrade performance by preventing the incoming signal from reaching the junction resistance where the mixing takes place. Analysis of the voltage and current division shows that the loss in dB, at incoming frequency ω , is:

$$10 \log \left(1 + \frac{R_S}{R_j} + \omega^2 C_j^2 R_S R_j \right)$$

This effect is shown by comparing performance of diodes with different values of capacitance and series resistance.

Local Oscillator Power Level

The two mixing signals are the local oscillator and the input signal. The measure of performance is the conversion loss, the ratio of output power to the power of the input signal. The local oscillator power level influences the conversion loss. This effect will be shown for the 5082-2817 diode.

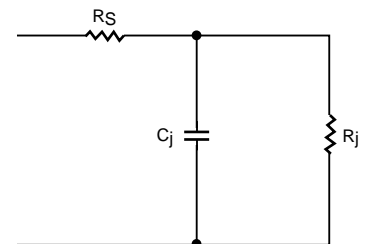


Figure 1. Equivalent Circuit

Spurious Response

Although mixing has been described as the production of the difference frequency from two inputs, the nonlinear characteristic of the diode also produces the sum frequency and sum and difference frequencies of harmonics of the local oscillator and incoming frequencies. Results of a study of these effects will be shown.

Effects of DC Bias and Local Oscillator Power Level

Figure 2 shows the conversion loss of a 5082-2817 mixer diode measured at 2 GHz. The top curve was measured without DC bias. Optimum DC bias was applied at each level for the bottom curve. The curves meet at the optimum local oscillator level where bias does not help. Below this level forward bias is used. Above this level reverse bias is used to reduce the rectified current.

At low levels of L.O. power, the conversion loss degrades rapidly unless DC bias is used. At -10 dBm the degradation is about 7 dB from the performance at the standard 0 dBm power level. Replacing the lost L.O. power with DC bias recovers about 5 dB of the degradation.

At high levels of L.O. power the performance degrades again. This is caused by the rapid increase of junction capacitance. Reverse bias reduces the current and the capacitance, restoring the diode performance.

Capacitance and Series Resistance

The effect of junction capacitance and series resistance was studied by comparing conversion loss data measured with three diodes covering a wide range of these parameters. The 5082-2800 is a general purpose diode, typically used in clamping circuits.^[2] The 5082-2817 is a 2 GHz mixer diode. The 5082-2755 is a 10 GHz detector diode. Figure 3 shows the conversion loss measured at 2 GHz for these three diodes.

The 5082-2800 general purpose diode has a conversion loss several dB worse than that of the other diodes. This is expected because this diode has a higher junction capacitance.

The behavior of the low capacitance 5082-2755 detector diode is more interesting. At local oscillator power levels below -3 dBm the conversion loss is better than the loss of the 5082-2817 mixer diode, but at higher power levels it is worse.

A good approximation to the effect of junction capacitance and series resistance on conversion loss is:

$$L_1 = 1 + \frac{R_S}{R_j} + \omega^2 C_j^2 R_S R_j$$

This is the ratio of available power to the power delivered to the junction resistance, R_j , using the diode equivalent circuit of Figure 1.

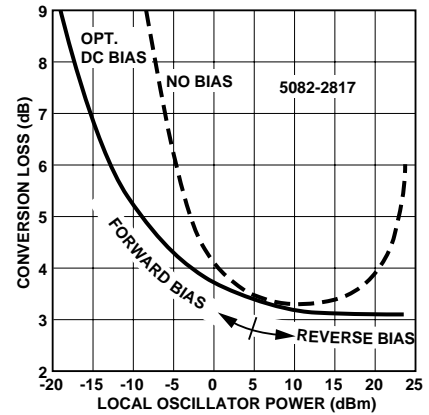


Figure 2. Effect of DC Bias on Conversion Loss

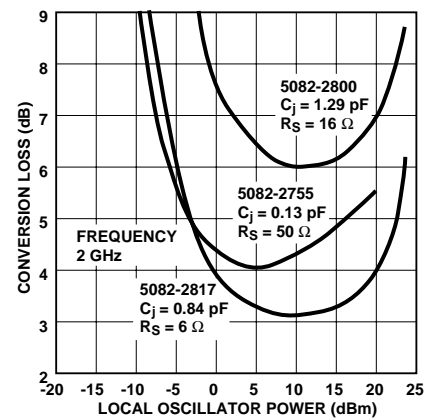


Figure 3. Effect of Capacitance and Series Resistance on Conversion Loss

The value of junction capacitance varies with voltage as:

$$C = \frac{C_o}{\sqrt{1 - \frac{V}{0.6}}}$$

where 0.6 is a typical value of barrier voltage.

The relative values of conversion loss in Figure 3 may be explained by these equations. Zero bias capacitances for the three diodes were measured to be 0.84 pF, 1.29 pF, and 0.13 pF for the -2817, -2800, and -2755 diodes respectively.

At a local oscillator power level of 1 milliwatt the forward current is about 1 milliampere. Using the corresponding forward voltages, C_j is computed for the three diodes. Assuming a junction resistance of 150 ohms, reasonable values of series resistance may be chosen to make the relative values of L_1 correspond to the relative measured values.

The familiar junction resistance equation $R_j = 26/I$ does not apply for $I =$ rectified current. It refers to $I =$ D.C. bias current. When rectified current is 1 mA, instantaneous current varies over forward and reverse values. Junction resistance is very large when the current is negative so the average junction resistance is larger than predicted by this equation.

Diode	C_j (pF)	R_S (ohms)	L_1 (dB)
-2817	1.3	6	1.07
-2800	2.2	16	4.68
-2755	0.24	50	1.47

At -3 dBm the -2817 and -2755 curves cross, with the -2800 loss 4.5 dB higher. This relative loss can be explained by raising R_j to 235 ohms and decreasing the capacitance values.

Diode	C_j (pF)	L_1 (dB)
-2817	1.12	1.2
-2800	2.1	5.7
-2755	0.23	1.2

These values of C_j and R_S were chosen to illustrate the effect on conversion loss. Since saturation currents are different for these diodes and junction resistances may be different, the actual values of C_j and R_S may be somewhat different.

The L_1 equation shows the loss behavior with frequency. At low frequencies the loss is independent of frequency and capacitance. Choosing a low value of series resistance provides the best diode. At high frequencies low capacitance becomes more important than low series resistance because capacitance is squared in the L_1 equation.

Figure 4 shows L_1 vs. frequency for the 5082-2835 diode with $R_S = 6$ ohms and $C_j = 1.0$ pF and for the HSCH-5310 diode with $R_S = 17$ ohms and $C_j = 0.1$ pF. The lower capacitance makes the -5310 the better diode at microwave frequencies while the lower resistance makes the -2835 the better diode at low frequencies.

The Effect of Barrier Voltage

The type of metal deposited on silicon to form a Schottky barrier influences the barrier voltage [3] which is involved in the saturation current determining the forward current. We use the term low barrier for diodes with low values of voltage for a given current (usually 1 mA). We have previously shown the effect of barrier voltage on the variation of junction capacitance with forward voltage.

Figure 5 shows the measurement of conversion loss for two diodes having a range of barrier potential values.

Diodes	Barrier Potential
5082-2817	0.64
HSCH-3486	0.35

At low L.O. power levels the lower barrier diode has better performance. At higher power levels this diode loses its advantage because of higher series resistance.

Effect of Load Resistance

Figure 6 shows the effect of mixer load resistance on conversion loss. At low local oscillator power levels the effect is similar to the barrier effect. More rectified current flows with smaller load resistance so performance is better. At higher power levels the degradation due to higher capacitance appears first with the lower load resistances. As a result the optimum value of load resistance increases with L.O. power level. At +9 dBm 100 ohms becomes better than 10 ohms. At +19.5 dBm 400 ohms becomes better than 100 ohms.

The load circuit can be designed to provide the optimum resistance as the local oscillator power level changes. [4]

Harmonic Distortion

Sums and differences of multiples of the two mixing frequencies are produced in the mixing diode. These frequencies appear as spurious responses in the output. This effect was studied by setting the signal frequency at 2 GHz and the power at -30 dBm. The local oscillator was then set at various frequencies to produce harmonic mixing with a difference frequency of 30 MHz. Local oscillator power was one milliwatt. Then the local oscillator was set at 2 GHz and the signal frequency varied. The output levels in dB below fundamental mixing are shown in Figure 7. The diode was placed in a 50 ohm untuned coaxial mount.

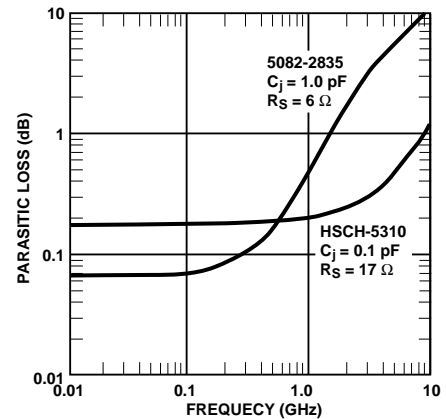


Figure 4. Parasitic Loss

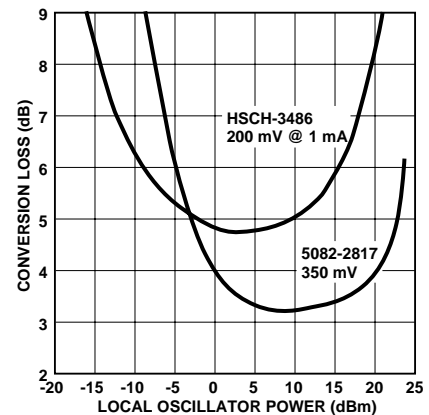


Figure 5. Effect of Barrier on Conversion Loss

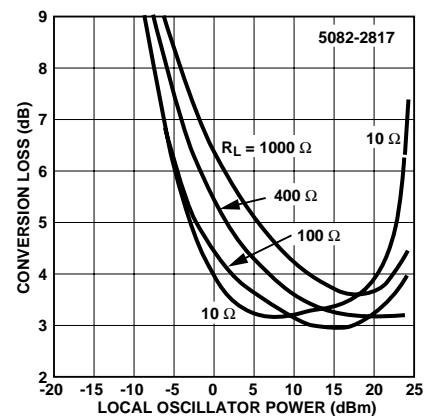


Figure 6. Effect of Load Resistance on Conversion Loss

The output levels of the m1 products, mixing of the signal fundamental with multiples of the local oscillator, are much higher than the 1n products, mixing of the local oscillator fundamental with multiples of the signal. For example, the 2 x 1 output is 5 dB below fundamental. Figure 5 shows that this level of fundamental mixing corresponds to a local oscillator level of -8 dBm. The doubling efficiency was about 8 dB. The 1 x 2 output is 16 dB below fundamental mixing. This corresponds to a signal level of -46 dBm. The doubling efficiency is 16 dB for the lower level signal frequency. Although fundamental mixing in Figure 5 was measured in a tuned system and the data of Figure 7 was measured in an untuned system, this analysis nevertheless gives a comparison of multiplying at the one milliwatt and one microwatt power levels. Mixing of signal multiples above 2 with local oscillator multiples above the fundamental produced outputs below the -100 dBm sensitivity of the receiver.

4	19	39	X	X
3	13	38	X	X
2	5	45	56	42
1	0	16	21	43
	1	2	3	4
	SIGNAL			

Figure 7. Harmonic Distortion

Two Tone Distortion

Harmonic distortion may be suppressed by a band pass filter at the mixer input. When the distortion is caused by:

$$mf_{LO} - nf_S = f_{if}$$

the unwanted frequency is:

$$f_S = \frac{m}{n} f_{LO} - \frac{f_{IF}}{n}$$

The narrowest filter required corresponds to $m = n = 2$ with a rejection bandwidth equal to the intermediate frequency.

Two tone distortion is the result of two unwanted signals mixing with each other and the local oscillator to produce an intermediate frequency output. The equation is:

$$f_{LO} - mf_1 + nf_2 = f_{IF}$$

Third order two tone intermod may correspond to $m = 2, n = 1$. In this case the correct intermediate frequency is produced when the desired signal f_S equals $2f_1 - f_2$. The unwanted frequencies may be arbitrarily close to the desired frequency so the problem cannot be solved with a filter.

Third order two tone distortion in a 5082-2817 diode was investigated with a local oscillator frequency of 1.94 GHz and input frequencies of 2 GHz and 1.985 GHz. The intermediate frequency was $2 \times 1.985 - 2 - 1.94 = 0.03$ GHz. The measure of distortion is the input intercept point, the power level where the line of output vs. input power for the desired mixing intersects the extension of the spurious line. This is shown in Figure 8. Since the desired output is linear, the suppression of the spurious output is $2A$ and input intercept is input power plus half the suppression.

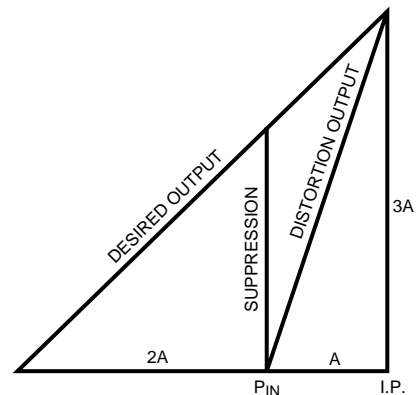


Figure 8. Intercept Point

With the help of this relationship intercept point was measured as a function of local oscillator power level. The results are shown in Figure

9. At higher local oscillator power levels the desired output increases while the spurious output decreases. This raises the suppression and the intercept point. At lower levels both desired output and spurious decrease so the intercept point levels off to a constant value.

Multiple Diode Mixers

Although the intermediate frequency may be produced by mixing in a single diode, very few mixers are made this way. The problems generated by using a single diode include radiation of local oscillator power from the input port, loss of sensitivity by absorption of input power in the local oscillator circuit, loss of input power in the intermediate frequency amplifier, and the generation of spurious output frequencies by harmonic mixing. Some of these problems may be solved by circuit techniques, but these circuits often introduce new problems. Most mixers use multiple diode techniques to better solve these problems.

Early mixer designs prevented loss of signal power in the local oscillator circuit by loosely coupling the local oscillator power to the mixer diode. This technique is wasteful of local oscillator power and it sends as much power to the input, possibly an antenna, as it sends to the diode. This local oscillator radiation could be interpreted as a target return when received by a radar. This problem may be alleviated by using a directional coupler to send the local oscillator power to the mixer diode. Coupling must be loose so that L.O. power is still wasted.

A balanced mixer (Figure 10) provides a better solution. The hybrid circuit splits the L.O. power to the two diodes with little coupling to the antenna. A low pass filter is needed to prevent loss of power to the intermediate frequency amplifier. Additional advantages are reduction of L.O. noise and harmonic mixing. L.O. noise is rejected because two signals originating in the same port produce I.F. outputs that cancel. This is a property of the hybrid circuit. Similarly, even order harmonics of either the L.O. or the signal produce cancelling outputs.

In the double balanced mixer (Figure 11) even order harmonics of both the L.O. and the signal frequency are rejected. This mixer does not require a low pass filter to isolate the I.F. circuit. The three ports are isolated from each other by the symmetry of the circuit. These mixers usually cover a broader band than the others. Ratios as high as 1000:1 are available. Microwave equivalents of these mixer circuits are available. Bandwidth ratios as high as 40:1 are available at microwave frequencies.

Intermodulation distortion is reduced [5] when local oscillator power is increased. Several design techniques are used to allow higher drive.

A higher barrier diode may be used to retain linear response at higher drive levels. More than one diode may be used in each arm of the ring in a double balanced mixer. This permits higher drive level without overheating the diodes. Two rings may also be used to increase the local oscillator level. This technique is also used for image tuning.

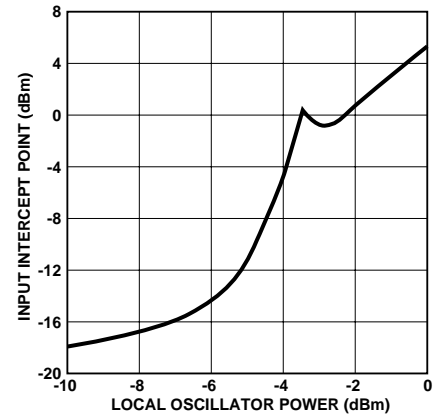


Figure 9. Two-Tone Distortion

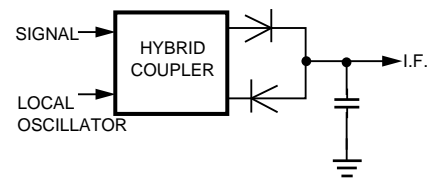


Figure 10. Balanced Mixer

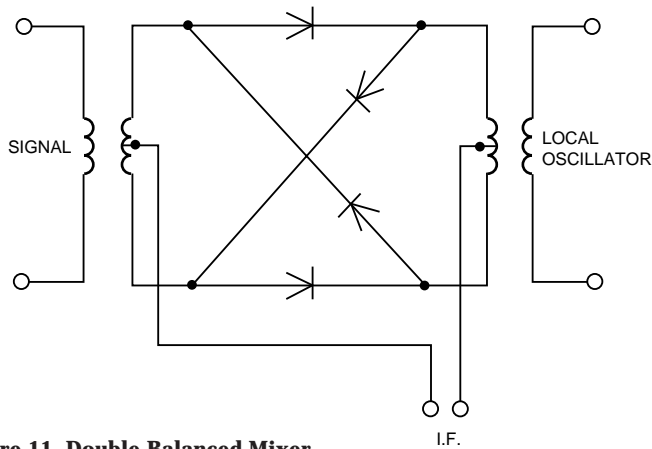


Figure 11. Double Balanced Mixer

Tuning for Better Sensitivity

The ideal mixer should convert all of the signal power to output power at the desired output frequency. However, it is customary to test diodes in a broadband mixer circuit. In this test no attempt is made to recover the power lost in the unwanted output frequencies. Because of these losses and the losses in the diode parasitics, an efficiency of about 35% is usually achieved.

Special circuits have been developed to improve this figure to come closer to the ideal 100% efficiency. The most serious spurious response, called the image response, produces an output at the frequency $2f_{LO} - f_S$. Image recovery mixers are designed to recover this lost power. Two dB improvement has been reported.^[6] By properly terminating harmonics up to the third, conversion loss under 2 dB was obtained with a Hewlett-Packard beam lead diode. ^[7]

Harmonic Mixing

While harmonic products are usually considered spurious, in some designs the desired output is the result of harmonic mixing. This is a valuable mixer technique when the frequency is so high that it is difficult to generate the local oscillator power. Hewlett-Packard Application Note 991, *Harmonic Mixing With the HSCH-5500 Series Dual Diode*, describes a technique using the 2nd harmonic of the local oscillator with little loss of efficiency compared to fundamental mixing. Mixers using the 6th, 8th, and 10th harmonics are used to extend the range of Hewlett-Packard spectrum analyzers to 60 GHz. ^[8]

SUMMARY

Schottky diode mixing efficiency is related to both diode parameters and circuit parameters. Diode parameters studied include capacitance, resistance, and barrier voltage. Circuit parameters include DC bias and load resistance.

Harmonic response and third order two tone intermodulation were also studied.

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