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Predicting Intermodulation Suppression in Double-Balanced Mixers

Predicting intermodulation (IM) suppression in double-balanced (DB) mixers continues to be extremely important in the design and operation of microwave and RF systems. IM products generated by the mixer can masquerade as the down-converted IF signal, thereby reducing system effectiveness. Fortunately, the threat of IM products can be avoided if their frequencies and power levels are known. Determination of IM frequencies is fairly simple, but knowledge of the exact power levels of IM products generated by mixers always requires careful measurement, which is time consuming and, thus, expensive. Approximate predictions of IM power levels are sometimes deducible from catalog data showing trends in typical IM suppression for a given mixer; but often, such data is unavailable. Various efforts have been made to mathematically predict IM suppression in single-ended and single-balanced mixers[1, 2], but to date no practical formulas for DB mixers have been made available. To help microwave and RF system designers predict single-tone IM suppression, some simple rule-of-thumb formulas that generally agree with measured data are presented in Table 1. The formulas in the right-hand column come from equation 1 (see page 3 and appendix), which is based on the switching characteristics of four ideal diodes. The formulas in Table 1 are unique in that they predict IM suppression, given only ΔP (the difference between RF and LO power levels).

Also included in this article is a practical four-step method to reduce the effect of intermodulation products (intermods) on the system by optimizing mixer usage. With a reliable approximation of suppression for a given IM product, the system designer can better choose the mixer input and output frequencies that minimize the presence of poorly suppressed IM products in the IF output passband. Furthermore, distinguishing a particular IM product from others on a crowded spectrum analyzer display is easier when the approximate level of the desired product is known.

The expressions for IM suppression presented in Table 1 are calculated from equation 1 by using nominal values of balun imbalance, diode mismatch, and V_F (diode turn-on voltage). Equation 1 represents the generalized formula for IM suppression for various values of these parameters. The derivation of the equation is based on the switching characteristic of an ideal diode and, as a result, mixing caused by normal diode nonlinearity is ignored. This approximation has been addressed in the literature[3], and is justified ostensibly by the close agreement between calculated and measured IM suppression, as long as the values of n and m are small, and ΔP is less than about -15 dB. The approximation is made in the analysis that the RF power is much less than the LO power. When n, which is the harmonic of the high-level (LO) input is less than 8, and m, which is the harmonic of the low-level (RF) input is less than 4, predicted results are accurate enough for most system design applications. For larger values of n and m, calculated suppression tends to be better than actual suppression. Evidently, approximations made in the derivation begin to cause inaccuracies for higher values of n and m.

(LO) n	(RF) m	S_{nm} Suppression (dBc)
1	1	0
1	2	ΔP-41
1	3	2ΔP-28
2	1	-35
2	2	ΔP-39
2	3	2ΔP-44
3	1	-10
3	2	ΔP-32
3	3	2ΔP-18
4	1	-35
4	2	ΔP-39
5	1	-14
5	3	2ΔP-14
6	1	-35
6	2	ΔP-39
7	1	-17
7	3	2ΔP-11

Table 1. Formulas approximating suppression of certain IM products. n corresponds to the high-level (LO) input, and m corresponds to the low-level (RF) input. $\Delta P = P_{RF}$ (dBm) - P_{LO} (dBm).

The expressions given in Table 1 are valid whether n and m are positive or negative. The frequencies of IM products in Table 1 are assumed to be within the mixer IF output bandwidth.

Table 1 is used as follows: Suppression of any product listed is approximated by subtracting the LO input power, in dBm, from the RF input power, in dBm, to get ΔP, which is then used to calculate IM suppression. For example, when the LO power is +10 dBm and the RF power is -20 dBm, ΔP = -30 dB, and the $\pm nf_L \pm mf_R$ IM product, when both n and m equal 2, is suppressed by approximately {ΔP - 39} dBc, or -69 dBc. The suppression of the 2 × 1 product will be about -35 dBc. In the following paragraphs, $\pm nf_L \pm mf_R$ is abbreviated to n × m (referred to as, "n by m").

The formulas in Table 1 agree with the (m-1) rule[4]; namely, that decreasing RF input power by K dB results in an increase of suppression of any n × m product by K*(m-1) dBc. The formulas in Table 1 also imply that the same is true for an increase in LO power because ΔP becomes more negative when LO power is increased, as well as when RF power is decreased. But, in practice, IM sup-

Author: Bert C. Henderson

pression is more accurately predicted using the (m-1) rule for changes in RF power than for changes in LO power. As expected, calculated suppression of products with m = 1 remains fixed as ΔP varies.

The formulas in Table 1 are based on a double-balanced (DB) mixer with circuit balance and diode match that are generally representative of microwave mixers. Hence, IM suppression calculated using Table 1 is approximate, and may deviate from actual measurement depending on the mixer, the frequencies involved, and load conditions. To get a sense of accuracy of these formulas, measured values of IM suppression for various types of mixers are compared with calculated values.

COMPARISON WITH MEASURED DATA

Table 2 indicates that equation 1 and Table 1 are useful in predicting IM suppression because predicted values of suppression generally fall within the variance of measured suppression for the various classes of mixers. **[For definitions of diode mixer classes, see "Mixers Part 2: Theory and Technology", Bert Henderson, 1981. -Ed.]**

ODD × ODD IM PRODUCTS

Table 2 shows that predicted suppression for, ΔP = -20 dB, generally agrees with measured data for various classes of mixers, especially for odd × odd and even × even TM products. For example, the 3 × 1 product is predicted to be -10 dBc, which agrees closely with measured values of -10 dBc to -12 dBc for the lower-frequency mixers. These values probably would be closer to predicted values if a higher LO power were applied. Careful study of 3 × 1, 5 × 1, and 7 × 1 IM data, taken with a varying LO power level, [8] shows that these particular products are better suppressed when LO power is slightly lower than that required for optimum conversion-loss, but reducing LO power also degrades suppression of IM products when m ≥ 2.

Hence, odd × odd products, especially with m = 1, should never be allowed inside the IF bandwidth because virtually nothing can be done to improve their suppression without degrading suppression of other products.

The 3 × 3 product is predicted to have suppression of -58 dBc, agreeing with measured values in Table 2, ranging from -65 dBc to -50 dBc. The 5 × 3 product is predicted to have suppression of -54 dBc, which is at least centered among measured values ranging from -47 dBc to -69 dBc.

EVEN × EVEN IM PRODUCTS

Besides odd × odd products, calculated values of even × even IM suppression generally conform to measured data. Calculated suppression of 2 × 2 products for, ΔP = -20 dB, is -59 dBc, which generally agrees with data ranging from -50 dBc to -64 dBc. Suppression of 4 × 2 and 6 × 2 products is predicted to be the same as for 2 × 2 products; i.e., -59 dBc, which also agrees with measured values of -50 dBc to -66 dBc and -52 dBc to -67 dBc, respectively.

Data in Table 2 indicates that suppression of even x even IM products in DDB and Class IV mixers is generally better than in DB Class I, II and III mixers. This is because all three ports of DDB and Class IV mixers are balanced, whereas only two ports, generally the L- and R-ports, are balanced in DB mixers.

EVEN × ODD AND ODD × EVEN IM PRODUCTS

Calculated values of even × odd and odd ×

IM Product		DDB						Class IV		Class I				Class II Type I				Class II Type II		Class III		Predict. Values
n	m	M50A		M89		M2T		M4T		M79		M6V		M9C		M79H		M9BC		M9E		(ΔP = -20)
1	1	0	6	0	7	0	8	0	1	5	0	0	1	0	1	0	5	0	1	0	1	0
1	2	55		51		64		61		60		50		63		63		63		59		61
1	3	>60		>65		64		66		60		60		60		62		65		63		68
2	1	35		30		41		43		42		30		35		40		41		50		35
2	2	60		54		61		64		60		55		50		62		60		51		59
3	1	19		16		10		12		12		11		11		12		10		12		10
3	2	>58		60		60		60		42		49		61		48		58		59		52
3	3	63		62		58		61		>60		58		57		65		50		57		58
4	1	41		40		50		45	2	35		41	2	32		32		39	2	39	2	35
4	2	>62		60		57		66		—		55		57		—		56		50		59
5	1	30		34		30		16		25		18		15		20		15		28		14
5	3	—		64		54		54		>60		53		50		69		54		47		54
6	1	45		—		48		49		—		56		41		—		50		37		35
6	2	62		55		66		67		—		56		59		—		63		52		59
7	1	33		35		18		21	3	24		25	3	19		22		19	3	21	3	17
7	3	>60		>65		55		54	2	—		25	2	54		—		50	2	50	2	51
		P_{LO} = +10 dBm P_{RF} = -10 dBm												P_L = +20 dBm P_R = 0 dBm								

Notes	1	2	3	4	5	6	7	8
f_L (MHz)	200	180	125	150	2900	4100	2000	275
f_R (MHz)	180	400	400	49	7100	6000	3250	200

Table 2. Comparison of various IM products and classes of mixer.

Author: Bert C. Henderson

even suppression generally agree with measured values as well. 1 × 2 and 2 × 1 products are predicted to have -61 dBc and -35 dBc of suppression, respectively, which approximately agree with the measured values of -50 to -64 dBc and -30 to -50 dBc, respectively. Measured suppression of 2 × 1, 4 × 1, 6 × 1,..., etc. IM products are similar for a given mixer, as predicted.

GENERALIZED EQUATION FOR IM SUPPRESSION

The results in Table 1 were calculated using equation 1, which gives IM suppression in dBc for various values of circuit balance, diode match and RF and LO power levels.

Equation 1

$$S_{nm} \triangleq \text{IM Suppression (dBc)} = (|m| - 1)\,\Delta P + 20\log(|A_{nm}|) \qquad (1)$$

$$A_{nm} = \frac{1}{B_{IF}\,|m|!}\left[\frac{\Gamma\left(\frac{|n|+|m|-1}{2}\right)}{\Gamma\left(\frac{|n|-|m|+3}{2}\right)}\,\frac{1}{2}\left\{\sin\frac{|n|\pi}{2}\sin\frac{|m|\pi}{2}B_{oo}+\cos\frac{|n|\pi}{2}\cos\frac{|m|\pi}{2}B_{ee}\right\}+\ldots\right.$$

$$\left.\ldots+\frac{\Gamma\left(\frac{|n|+|m|}{2}\right)}{\Gamma\left(\frac{|n|-|m|+2}{2}\right)}\,V_f\left\{\sin\frac{|n|\pi}{2}\cos\frac{|m|\pi}{2}B_{oe}+\cos\frac{|n|\pi}{2}\sin\frac{|m|\pi}{2}B_{eo}\right\}\right]$$

$\Gamma(k+1) = k\Gamma(k)$, $V_f = V_F/V_L$

$B_{oo} = 1 + \delta_4 + \alpha(\delta_3 + \delta_2) - |m|\,\{\delta_4 - \delta_2 + \alpha(\delta_3 + \delta_2) - \beta(\delta_3 + \delta_4)\}$; odd × odd

$B_{ee} = -1 + \delta_4 - \alpha(\delta_3 - \delta_2) - |m|\,\{\delta_4 - \delta_2 - \alpha(\delta_3 - \delta_2) + \beta(\delta_3 - \delta_4)\}$; even × even

$B_{oe} = |m|\,\{-\delta_4 - \delta_2 + \alpha(\delta_3 + \delta_2) + \beta(\delta_4 - \delta_3)\}$; odd × even

$B_{eo} = |m|\,\{\delta_4 + \delta_2 + \alpha(\delta_3 - \delta_2) - \beta(\delta_4 + \delta_3)\}$; even × odd

$B_{IF} = B_{oo}$ with m = 1

$\Delta P = P_{RF}\,(\text{dBm}) - P_{LO}\,(\text{dBm})$

$\delta_2 = \dfrac{V_2}{V_1}$, $\delta_3 = \dfrac{V_3}{V_1}$, $\delta_4 = \dfrac{V_4}{V_1}$ (See Figure 2)

L-Balun Isolation = $20\log(1 - \alpha)$
R-Balun Isolation = $20\log(1 - \beta)$ (See Figure 1)

The parameters alpha and beta in equation 1 are measures of L- and R-port imbalance, respectively. Beta is the ratio of the voltage-to-ground at the two points where the R-port balun ties to the diodes; alpha is the same for the L-port balun. Both alpha and beta ideally equal 1, but parasitics and other nonideal factors can cause alpha and beta to equal values ranging from 0.7 to 0.8, calculated from typical balun isolation of 10 to 15 dB, respectively, as shown in Figure 1 for beta. Results in Table 1 are based on alpha and beta both being equal to 0.7.

Besides balun imbalance, the analysis considers diode voltage mismatch as caused by impedance variations amongst the four diodes. This is due to differences in diode capacitance, C_T, and series resistance, R_T, of each of the four diodes. These voltage differences are approximated by weighting each of the ideal diode voltages, with their respective values of diode impedance normalized with respect to the impedance of diode 1. Diode voltages V_2 through V_4 in Figure 2 are multiplied by δ_2, through δ_4, respectively, which are the ratios of the voltages across diodes 2 through 4, to the voltage across diode 1 (ideally, $\delta_2 = \delta_3 = \delta_4 = 1$). Table 1 is based on $\delta_2 = 0.85$, $\delta_3 = 0.95$ and $\delta_4 = 1.05$.

The formulas in Table 1 are calculated from equation 1 using the approximation that δ_2 through δ_4, and alpha and beta are constant as a function of frequency. This is reasonable because the IM products of most interest are close to the IF output frequency.

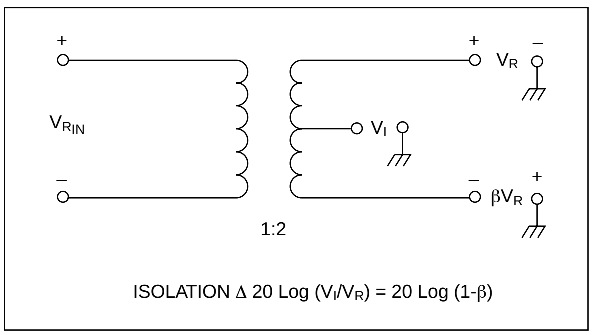


Figure 1. Balun imbalance as a function of β.

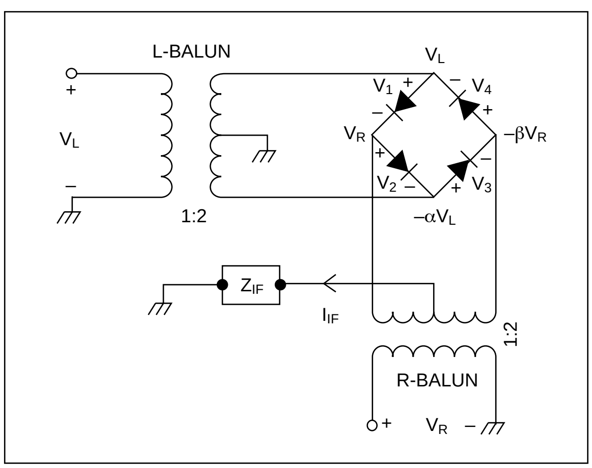


Figure 2. Double-balanced mixer.

V_f, which equals V_F/V_L (V_L is the peak LO voltage), is present in the odd × even and even × odd portions of equation 1, but NOT in the odd × odd and even × even portions. This helps explain why measured values of odd × odd and even × even IM suppression tend to agree with calculated values better than odd × even and even × odd values: V_f is an approximate value because both V_L, and especially, V_F, are approximate values. Table 1 is based on V_F = 0.1, assuming V_F - 0.3 volts, and V_L = -3.0 volts corresponding to +20 dBm of LO power in a 50-ohm system.

V_F affects suppression of all IM products because a higher V_F allows more LO power to be applied to the mixer, increasing $|\Delta P|$, assuming RF power remains constant, and thus increasing suppression of all four types of IM products. Equation I indicates that increasing V_F without commensurately increasing LO power will tend to reduce suppression of odd × even and even × odd products, but not affect odd × odd and even × even products. Thus, it is important to consider the interrelationship between LO power, diode forward voltage, and suppression of the various IM products.

To illustrate the use of equation 1, suppression of the 3 × -2 product is calculated:

Example Calculation: 3 × -2

Using $\alpha = \beta = 0.7$, $\delta_2 = 0.85$, $\delta_3 = 0.95$, $\delta_4 = 1.05$. $V_f = 0.1$, $B_{IF} = 3.25$, $B_{oe} = -1.14$

$|A_{nm}| = [1/(3.25)(2)]\ [\Gamma(5/2)/\Gamma(3/2)]\ (0.1)\ (1.14) = 0.026$

$S_{nm} = [\Delta P - 32]$ dBc

IMPORTANT RULES FOR IM SUPPRESSION

Equation 1 provides significant insight into the suppression of IM products. It agrees with the well-known fact that IM suppression is best when LO power is high and RF power is low i.e., when $|\Delta P|$ is maximum. Also, suppression of products with even harmonics is best when mixer circuitry is well-balanced and diodes are well matched, which is manifested by high interport isolation due to circuit balance.* Also, circuit balance and diode match must be commensurate with each other because IM suppression may not increase if the diode match is improved, while circuit balance remains poor.

Equation 1 confirms that even × even products are best suppressed when both L- and R-ports are well balanced and all four diodes are well matched. These same conditions minimize conversion loss (the 1 × 1 product), as well as suppression of odd × odd IM products. Odd × even products are best suppressed when the L-port balun is well balanced ($\alpha = 1$) and the diodes across it are well matched ($\delta_3 = \delta_4$). Even × odd products are best suppressed when the R-port balun is well balanced ($\beta = 1$) and the diodes across it are well matched ($\delta_2 = \delta_3$). The general rule-of-thumb to remember is that best suppression of odd × even and even × odd products is obtained when the LO and RF inputs, respectively, are injected into well-balanced ports. The optimum arrangement is to inject both LO and RF signals into well-balanced ports to best suppress odd × even and even × odd products.

DOWNCONVERTING AND UPCONVERTING

In double-balanced mixers, two of the three ports are balanced at the diodes, and the third port, which is unbalanced, almost always operates at lower frequencies to serve as the IF output. Therefore, injecting the LO and RF signals into the balanced ports generally corresponds to the downconverting case in which the bandwidths of two balanced ports are higher in frequency than the unbalanced IF output port. This explains why IM suppression is usually better when downconverting, as compared to upconverting, where either the RF or LO signal is injected into the unbalanced port. In the upconverting case, a low-frequency signal, injected into the unbalanced I-port is mixed with a second signal that is higher in frequency, and injected into the balanced R- or L-port. These two inputs produce an upconverted signal which exits the mixer via the third port.

FOUR-STEP OPTIMIZATION PROCEDURE

There are two possible ways to configure a DB mixer as an upconverter: Case 1, where the LO (high-level input) is injected into the mixer at the unbalanced I-port; and, Case 2, where the LO is injected at the balanced R- or L-port, as depicted in Table 3. IM suppression for Cases 1 and 2 are different, so the mixer configuration must be chosen carefully to optimize overall IM suppression. A systematic procedure to choose between Cases 1 and 2 follows:

1. Choose the low input frequency, f, and the high input frequency, F.
2. Determine which IM products (n × m) will exist inside the IF-output pass-band. This is usually done with a computer-generated IM chart.
3. a) Determine suppression for Cases 1 and 2 using n and in from step 2 and Table 1.

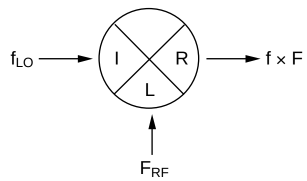
   b) Reduce predicted suppression by 10 dB for products having suppression that is below normal, as per Table 3. (The reduction factor of 10 dB causes measured upconversion IM suppression to agree with the predicted values, by taking into account the imbalance at the I-port.)
4. Decide whether Case 1 or Case 2 gives the best overall IM suppression.

CASE STUDY

We consider as a case study a Class II, Type

* In many instances, high interport isolation also results from filtering and cross-polarization of LO, RF and IF fields, due to orthogonal MIC baluns.

CASE 1 (f x F)			CASE 2 (F x f)		
f	F	Suppression	f	F	Suppression
EVEN ×	ODD	Normal	ODD ×	EVEN	Normal
ODD ×	EVEN	Below Normal	EVEN ×	ODD	Below Normal
DB MIXER			DB MIXER		



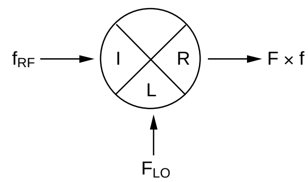


Table 3. Mixer configurations for upconverting Cases 1 and 2. F is the High Frequency Input, and f is the Low Frequency Input.

I DB diode mixer covering 6 to 18 GHz, used as an upconverter. IM suppression is measured for Case 1 (the LO injected into the unbalanced I-port at the low frequency) and for Case 2 (the LO injected into the balanced R-port at the high frequency). The LO level for this measurement is +20 dBm and the RF level is 0 dBm, so, ΔP = -20 dB.

Step 1

The low frequency is chosen to be f = 2.9 GHz, and the high-frequency range is chosen to be F = 7.1 to 7.6 GHz. The IF output is, therefore, 10.0 to 10.5 GHz.

Step 2

Using an in-house computer program, the IM products shown in Table 4 were found to be near the IF passband.

Step 3

Calculated and measured values of IM suppression for Cases 1 and 2 are given in Table 5.

(f) n	(F) m	Output Frequency (GHz)
1	1	10.0-10.5
2	1	12.9-13.4
-1	2	11.3-11.5
-2	2	9.0-9.4
-4	3	9.7-11.2
6	-1	9.8-10.3

Table 4. Listing of IM products in or near the IF band for step 2.

Note that calculated and measured values agree fairly closely.

Step 4

Case 2 is chosen as having the best overall IM suppression because its -F + 6f product is much better suppressed (-60 dBc) than the 6f - F product (-42 dBc) in Class 1. This is important because the output frequency range of these two products is 9.8 to 10.3 GHz, which overlaps the IF bandwidth of 10.0 to 10.5 GHz. If the -F + 6f and 6f - F products did not overlap the IF bandwidth, Case 1 would probably be the best choice because the -f + 2F product in Case 1, close to the IF pass band at 11.3 to 11.5 GHz, is much better suppressed (-50 dBc) than the 2F - f product in Case 2 (-26 dBc). The -4f + 3F and 3F - 4f products are ignored because of their high suppression, even though they overlap the IF bandwidth.

Using this method, the system designer can quickly arrive at the optimum upconverter configuration. He should then confirm these results with measured data, if possible. A similar process can also be used to determine the optimum downconverter arrangement, with Step 3b omitted.

DDB mixers can also be used as upconverters. These mixers generally have better even × odd or odd × even suppression than DB mixers because their I-port is balanced, but they tend to he slightly more expensive than DB mixers.

CONCLUSION

An analysis of DB mixers, based on the switching characteristic of an ideal diode, has been presented. The analysis predicts suppression of even × even, odd × even, even × odd, and odd × odd products. The effects of diode turn-on voltage, balun imbalance, diode mismatch, and RF and LO input power levels are considered. The analysis agrees with results already established by measured data; i.e., IM suppression is best when the mixer circuit is well balanced, the diodes are well matched, the LO power is highest, and the RF power is lowest.

Typical values of balun imbalance and diode mismatch are used to establish the simple rule-of-thumb expressions in Table 1 that predict suppression of various IM products, given only the difference between RF and LO power levels. Predicted IM suppression

Frequency (GHz)	Suppression (dBc)							
	Case 1				Case 2			
	(f) n	(F) m	Calculated	Measured	(f) n	(F) m	Calculated	Measured
10.0-10.5	1	1	0	0	1	1	0	0
11.3-11.5	-1	2	51	50	2	-1	25	26
12.9-13.4	2	1	35	40	1	2	61	63
9.0-9.4	-2	2	59	61	2	-2	59	63
9.7-11.2	-4	3	—	>60	3	-4	—	>60
9.8-10.3	0	-1	35	42	-1	6	—	>60

Table 5. Calculated and measured values of IM suppression for step 3.

values are within the range of measured IM suppression values for the various classes of mixers, and thus are accurate enough for many system design applications. Their accuracy can be enhanced by more closely tailoring values of circuit imbalance, diode mismatch and V_f to a particular mixer application.

In addition, a four-step procedure to choose the optimum port usage in mixers has been presented.

The analysis presented and the resulting formulas should be helpful to microwave and RF system designers working to avoid the presence of poorly suppressed IM products in their system IF bandwidths. These formulas also lend themselves to usage in computer simulations to approximate system IM performance as input frequencies and power levels to various mixers in the system are varied.

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