Characterization of Spurious-Response Suppression in Double-Balanced Mixers

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Abstract —A new analysis of spurious-response suppression in double-balanced (DB) mixers, using the diode current–voltage characteristic, is presented. A theoretical relationship between different spurious responses and the input power level is shown. This relationship leads to the following new conclusions: 1) a direct relationship exists between the spurious-response suppression and the spurious-response order of the RF component, and 2) a linear relationship exists between the spurious-response suppression and RF power. Experimental results are presented, showing close agreement with the above conclusions.

I. Introduction

HARMONIC MIXING between two frequencies f_L and f_R using a nonlinear element theoretically produces an infinite number of frequencies satisfying the condition

$$f_I = |\pm nf_L \pm mf_R| \qquad (1)$$

where f_I is the mixer intermediate frequency, f_L is the local oscillator frequency, f_R is the RF input frequency, n is the integer order of f_L, and m is the integer order of f_R. Normally, the desired products satisfy $n = m = 1$, and the other products are called spurious-responses. The prediction of spurious-response suppression in double-balanced (DB) mixers is a major concern to microwave designers. It is particularly important in broad-band receivers, phase-locked loops, and synthesizers.

Diodes are frequently used as the nonlinear elements in double-balanced mixers, and spurious-response prediction is based on the diode characteristics. The exponential resistive diode model was the first to be investigated. Pollack and Engelson [1] give approximate expressions that include only the influence of the local oscillator voltage and the nonlinearity coefficient and exclude the major influence of the RF level. Nitzberg [2] and Orloff [3] presents a general expression which includes all power series contributions up to a particular order product. Grestch [4] extends the mixing problem to the case of multiple CW inputs and then derives a general equation for the spectrum of each order of response.

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Herishen [5] does not use the coefficients of the exponential resistive diode model, but searches for other coefficients which include the effects of the circuit impedances and diode bulk resistance. His method requires complicated algebraic manipulation and he does not present a general expression for spurious-response suppression. Lepoff and Cowley [6] describes a technique to reduce intermodulation distortion in mixers. Gardiner and Yousif [7] use switching-function analysis to obtain distortion performance of diode modulators. Henderson [8] suggests a method based on the switching characteristics of a diode. His method considers the effect of diode turn-off voltage, balun imbalance, diode mismatch, RF and LO input power levels, and the cancellation effects of the mixer balance. Henderson's method agrees with the "$(m-1)$" rule, namely, that decreasing RF input power by K (dB) results in an increase of suppression of any $(n \times m)$ product by $K(m-1)$ (dBc). His formula implies that the same is true for an increase in LO power. This last claim, however, does not agree with measured data, and conflicts with the conclusions of Beane [9] and Maas [13], who showed that increasing LO power does not necessarily improve spurious-response supression. Advanced techniques for analyzing diode mixers are given by Egami [10], Held and Kerr [11], Faber and Gwarek [12], and Maas [13]. Their techniques consider the series resistance R_s, junction capacitance C_j, and lead inductance L_s, and they perform a nonlinear large-signal analysis of the local oscillator drive and then a linear small-signal analysis which takes into account RF input signal. Implementation of these techniques requires the use of special computer programs which are of limited availability to many designers.

As was indicated above, extensive efforts were made in order to find a precise prediction of the spurious-response suppression. However, measurements of spurious-response suppression performed on double-balanced mixers have shown great differences between similar mixers. Thus, it would appear that a theoretical prediction is not sufficiently useful.

In the present paper the exponential resistive diode model is used to characterize spurious-response suppression. The author believes that although this model is not fully precise, it is sufficient to define simple analytic expressions which yield some very important conclusions. By applying these expressions and taking a simple measurement, one can find spurious-response suppression at any input power (but sufficiently low relative to local oscillator power).

II. Single-Diode Mixer Analysis

In the present paper the diode is represented by the exponential resistive model:

$$i_D = i_0(e^{av} - 1) \tag{2}$$

where i_D is the current through the diode, v is the voltage across the diode, a is the nonlinearity coefficient, and i_0 is the saturation current. Using the Taylor expansion for e^x and substituting into (2),

$$i_D = i_0\left\{av + \frac{(av)^2}{2!} + \frac{(av)^3}{3!} + \cdots + \frac{(av)^n}{n!} + \cdots\right\}. \tag{3}$$

Assume for simplicity that the voltage across the diode is given by

$$v = V_L \cos\omega_L t + V_R \cos\omega_R t \tag{4}$$

where V_L is the voltage component of the local oscillator and V_R is the voltage component of the RF input. Substituting v from (4) into (3) determines all the spurious-response frequencies in the diode current:

$$i_D = i_0 \sum_{k=1}^{\infty} \frac{a^k}{k!}(V_L\cos\omega_L t + V_R \cos\omega_R t)^K. \tag{5}$$

From (5), one can see that any frequency current amplitude is given by an infinite sum of coefficients. Writing the amplitude coefficients of the desired $(f_L \pm f_R)$ using

$$(x+y)^k = x^k + \binom{k}{1}x^{k-1}y + \binom{k}{2}x^{k-2}y^2 + \cdots + \binom{k}{k}y^k \tag{6}$$

$$\cos^x y = \frac{1}{2^x}\sum_{z=0}^{x}\binom{x}{z}\cos(x-2z)y \tag{7}$$

$$\cos x \cos y = \frac{1}{2}\{\cos(x+y) + \cos(x-y)\} \tag{8}$$

we arrive at the amplitude of the desired signal:

$$i_{11} = i_0\left(\frac{a^2}{2!}V_L V_R + \frac{a^4}{4!}\cdot\frac{1}{2}V_L^3 V_R\left\{3 + 3\left(\frac{V_R}{V_L}\right)^2\right\} + \frac{a^6}{6!}\frac{1}{8}V_L^5 V_R\left\{15 + 45\left(\frac{V_R}{V_L}\right)^2 + 15\left(\frac{V_R}{V_L}\right)^4\right\} + \cdots\right). \tag{9}$$

Further, by applying the usual condition $V_L \gg V_R$ (experimentally $P_L - P_R > 15$ (dBc)), we obtain

$$i_{11} = i_0\left(\frac{a^2}{2!}V_L V_R + \frac{a^4}{4!}\frac{3}{2}V_L^3 V_R + \frac{a^6}{6!}\frac{15}{8}V_L^5 V_R + \cdots\right). \tag{10}$$

Identifying the general term for this series expansion, one may write the amplitude of the desired output components flowing through the diode as

$$i_{11} = i_0 V_R \sum_{k=1}^{\infty}\frac{a^{2k}}{2^{2k-1}}\frac{1}{(k-1)!k!}V_L^{2k-1}. \tag{11}$$

Repeating the above procedure for $|nf_L \pm mf_R|$ gives

$$i_{nm} = i_0 \frac{V_R^m}{m!}\frac{a^m}{2^{m-1}}\left(\frac{aV_L}{2}\right)^{n-2}\sum_{k=1}^{\infty}\left(\frac{aV_L}{2}\right)^{2k}\cdot\frac{1}{(k-1)!}\frac{1}{(k+n-1)!}. \tag{12}$$

Using a new index $k' = k-1$ and the equation

$$I_n(x) = \sum_{k=0}^{\infty}\frac{(x/2)^{n+2k'}}{k!\Gamma(n+k'+1)} \tag{13}$$

where $I_n(x)$ is the modified Bessel function of the order n, one may write

$$i_{nm} = i_0\frac{(aV_R)^m}{m!}\frac{1}{2^{m-1}}I_n(aV_L). \tag{14}$$

Equation (14) specifies the current amplitude of any spurious-response product present at a diode. Normalizing this amplitude to the amplitude of the desired output signal:

$$\frac{i_{nm}}{i_{11}} = \frac{1}{m!}\left(\frac{aV_R}{2}\right)^{m-1}\frac{I_n(aV_L)}{I_1(aV_L)} \tag{15}$$

and expressing the suppression in dBc, we arrive at

$$S_{nm}\ (\text{dBc}) = \left\{\log\left(\frac{1}{m!}\right) + (m-1)\log\left(\frac{aV_R}{2}\right) + \log I_n(aV_L) - \log I_1(aV_L)\right\} \tag{16}$$

where S_{nm} is the spurious-response suppression of the order $n \times m$. This expression was derived using simplifying assumptions which cannot be justified in every case; however it shows simple relationships which can lead to the following important conclusions:

1) The term $(m-1)\log(aV_R/2)$ defines the rule of "$(m-1)$," which means that increasing P_R by K (dB) will degrade the m-order products by $K(m-1)$ (dBc).
2) Suppression of the product of the order $n \times 1$ will be constant for any input power P_R. This conclusion is a special case of the $(m-1)$ rule.
3) The order m of a product specifies the suppression of that product, so that for larger m the suppression will increase. This property is due to the following two reasons:
   a) the term $1/m!$;
   b) the term $(aV_R/2)$ is usually smaller than one.
4) The order n of a product specifies the suppression of that product, and for larger n the suppression will increase. Fig. 1 shows the graphs of the modified Bessel functions of the orders 0–6. From Fig. 1, one can conclude that when n increases,

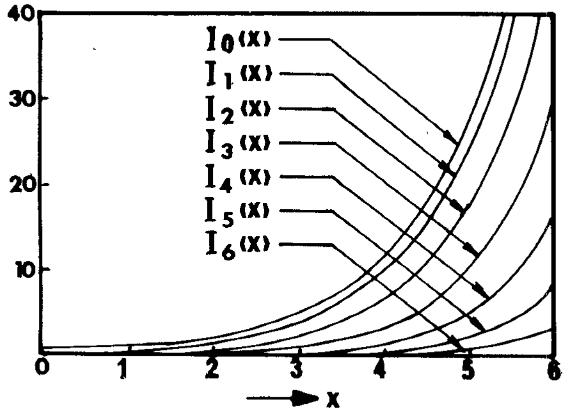


Fig. 1. Modified Bessel functions.

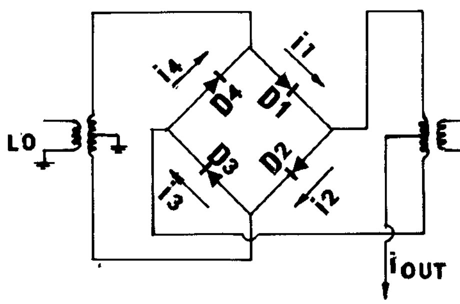


Fig. 2. Double-balanced mixer.

$I_n(x)/I_1(x)$ decreases and thus suppression is increased. This conclusion is usually correct.

5) The relation between the spurious-response suppression and the local oscillator power is given by the expression $I_n(aV_L)/I_1(aV_L)$.

From Fig. 1, one can conclude that for n orders greater than 1, increasing P_L will improve spurious-response suppression. This last conclusion has been known for many years to be usually correct, although not always so. Beane [9] and Maas [13] have shown that in some cases (depending on frequency and P_L power) increasing P_L will degrade spurious-response suppression. This phenomenon was explained in [9] to be an effect of series resistances and in [13] to be an effect of spectrum of components applied to the diode instead of a single sinusoid. In the present paper this phenomenon is not considered.

III. Double-Balanced Mixer Analysis

The analysis of double balanced-mixers is based on the single-diode mixer analysis and the special properties of the balanced structure. A four-diode double-balanced mixer is shown schematically in Fig. 2. From this figure the output current of the double-balanced mixer is

$$i_{\text{out}} = (i_1 - i_2) - (i_4 - i_3). \tag{17}$$

The $(n \times m)$ product of the currents i_1, i_2, i_3, and i_4 is given by

$$i_{nm} = i_0 \frac{(aV_R)^m}{m!} \frac{1}{2^{m-1}} I_n(aV_L) = C_m V_R^m I_n(aV_L) \tag{18}$$

where

$$C_m = i_0 \frac{a^m}{m!} \frac{1}{2^{m-1}}.$$

Multiplying the amplitude i_{nm} by $\cos(n\omega_L + m\omega_R)t$ gives

$$i_{nm} = C_m V_R^m I_n(aV_L) \cos(n\omega_L \pm m\omega_R)t. \tag{19}$$

Ideally the voltages V_L and V_R are the same for all diodes, but in fact they differ, due to the imperfect balance of the baluns, mismatches, and the diodes. In order to consider this difference, the following coefficients are defined:

$$\alpha_i = \frac{V_{R_i}}{V_{R_1}} \qquad \beta_i = \frac{V_{L_i}}{V_{L_1}}, \qquad i = 2,3,4$$

where V_{L_1} and V_{R_1} are the voltages across D_1. Using the coefficients α_i, β_i, one may write the $(n \times m)$ product of currents i_1, i_2, i_3, and i_4:

$$i_{nm_1} = C_m V_{R_1}^m I_n(aV_{L_1}) \cos(n\omega_L \pm m\omega_R)t \tag{20}$$

$$\begin{aligned} i_{nm_2} &= C_m V_{R_2}^m I_n(aV_{L_2}) \cos\{(n\omega_L \pm m\omega_R)t \pm m\pi\} \\ &= C_m \alpha_2^m V_{R_1}^m I_n(\beta_2 a V_{L_1}) \cos(n\omega_L \pm m\omega_R)t(-1)^m \end{aligned} \tag{21}$$

$$\begin{aligned} i_{nm_3} &= C_m V_{R_3}^m I_n(aV_{L_3}) \cos\{(n\omega_L \pm m\omega_R)t \pm (n+m)\pi\} \\ &= C_m \alpha_3^m V_{R_1}^m I_n(\beta_3 a V_{L_1}) \cos(n\omega_L \pm m\omega_R)t(-1)^{n+m} \end{aligned} \tag{22}$$

$$\begin{aligned} i_{nm_4} &= C_m V_{R_4}^m I_n(aV_{L_4}) \cos\{(n\omega_L \pm m\omega_R)t \pm n\pi\} \\ &= C_m \alpha_4^m V_{R_1}^m I_n(\beta_4 a V_{L_1}) \cos(n\omega_L \pm m\omega_R)t(-1)^n. \end{aligned} \tag{23}$$

Substituting (20)–(23) into (17) gives the total expression for the amplitude of the $(n \times m)$ product in a double-balanced mixer:

$$i_{nm} = i_0 \frac{a^m}{m!} \frac{V_R^m}{2^{m-1}} A_{nm}(\alpha_i, \beta_i, V_L) \cos(n\omega_L \pm m\omega_R)t \tag{24}$$

where

$$\begin{aligned} A_{nm} = \{ & I_n(aV_L) - (-1)^m \alpha_2^m I_n(\beta_2 a V_L) \\ & + (-1)^{n+m} \alpha_3^m I_n(\beta_3 a V_L) - (-1)^n \alpha_4^m I_n(\beta_4 a V_L) \}. \end{aligned}$$

Normalizing i_{nm} to i_{11},

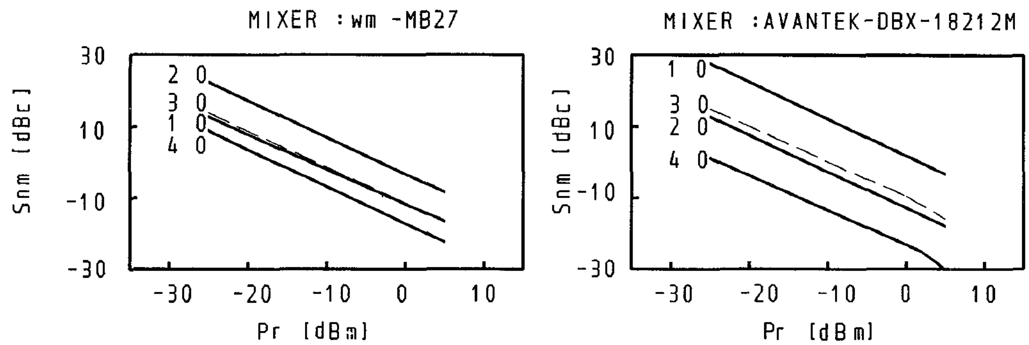
$$\frac{i_{nm}}{i_{11}} = \frac{1}{m!} \left(\frac{aV_R}{2} \right)^{m-1} \frac{A_{nm}}{A_{11}} \tag{25}$$

and expressing the suppression in dBc,

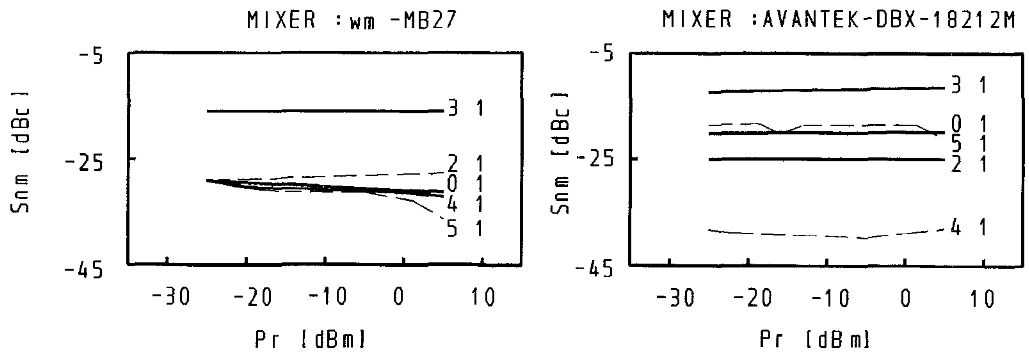
$$\begin{aligned} S_{nm}(\text{dBc}) = 20 \Big\{ & \log\left(\frac{1}{m!}\right) + (m-1)\log\left(\frac{aV_R}{2}\right) \\ & + \log A_{nm} - \log A_{11} \Big\} \end{aligned} \tag{26}$$

we arrive at the expression for spurious-response suppression in double-balanced mixers. This expression is a function of V_L, V_R, n, m, and the mixer balance, and leads to the following conclusions:

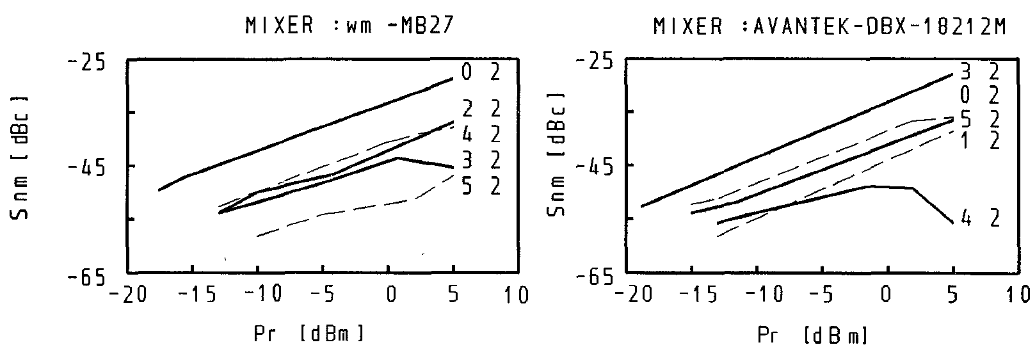
1) The rule of $(m-1)$ represents the influence of the input power P_R.
2) the order m of a product specifies the product suppression so that when m is larger the suppression increases.



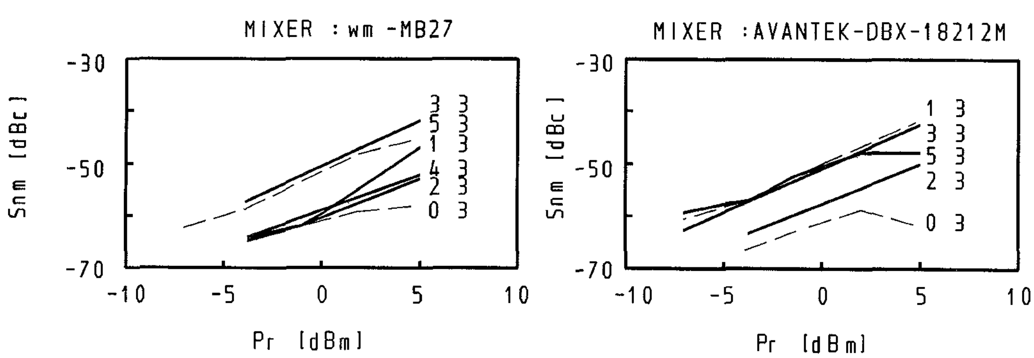
(a)



(b)



(c)



(d)

Fig. 3. (a) The measured $n \times 0$ products as a function of P_R with $P_L = 15$ dBm. (b) The measured $n \times 1$ products as a function of P_R with $P_L = 15$ dBm. (c) The measured $n \times 2$ products as a function of P_R with $P_L = 15$ dBm. (d) The measured $n \times 3$ products as a function of P_R with $P_L = 15$ dBm.

3) The term A_{nm} is a function of the mixer balance and has a great effect on the mixer spurious response. When m, n or both are even and $\alpha_i \to 1$, $\beta_i \to 1$ the term A_{nm} tends to zero; thus, spurious-response suppression improves. This well-known property is a result of the cancellation effect in a balanced mixer.

Equation (26) gives important information on the influence of the input power P_R and the order m, but it does not give obvious information on the influence of the local oscillator power P_L or the order n. The influence of these two parameters is given in A_{nm}, which is not a simple expression, and although the analysis uses simplified assumptions, no simple rules of thumb can be derived.

However, a knowledge of P_R and m and use of (26) can be very useful in the design of systems where P_L is fixed and P_R varies (in receivers, for example), or when a designer wants to evaluate the power of spurious-response products.

IV. Measurements

Measurements were performed on two double-balanced microwave mixers: an AVANTEK-DBX-18212M and a WM-MB27HX. Frequencies f_L and f_R were chosen to be 2.75 GHz and 2 GHz respectively in order to accommodate many spurious-response signals in the mixer output bandwidth. In all measurements the power P_L was set to its nominal value, and the power P_R was varied from -25 dBm to $+5$ dBm. The lower bound was chosen because at lower powers some spurious signals are very low and therefore difficult to measure. The upper bound was chosen to avoid saturation effects. All mixer responses were measured for each P_R power level, and the suppression (S_{nm} in dBc) was calculated.

Fig. 3(a) shows the measured results of $n \times 0$ products as functions of P_R with $P_L = 15$ dBm. One can see that the suppression of $n \times 0$ products in both mixers is a linear function of P_R with slope of -1 (i.e., $n \times 0$ suppression changes by K dB when P_R is varied by $-K$ dB). From Fig. 3(a), one may conclude that the mean suppression of $n \times 0$ products of both mixers is very similar and that with $P_R = 0$ dBm the mean suppression is -10.5 dBc. It can be seen that the linearity of the graphs exists provided $P_R < 0$ dBm.

Fig. 3(b) shows the measured results of $n \times 1$ products as functions of P_R with $P_L = 15$ dBm. One can see that the suppression of $n \times 1$ products in both mixers is constant provided that $P_R < 0$ dBm. From Fig. 3(b), the mean suppression of $n \times 1$ products of both mixers is very similar and with $P_R = 0$ dBm the mean suppression is -27.5 dBc for the WM mixer and -23 dBc for the AVANTEK mixer. Note that for both mixers the 3×1 product is the largest and that in the AVANTEK mixer the 5×1 product is larger than all other $n \times 1$ even products. This is due to inherent balance of the mixers.

Fig. 3(c) shows the measured results of $n \times 2$ products as functions of P_R with $P_L = 15$ dBm. The linear rule of $(m-1)$ is shown in these measurements and the suppression of $n \times 2$ products is a linear function of P_R with the slope of 1, provided $P_R < 0$ dBm. (Power measurement of a product as low as the noise level causes error in the measurement; therefore deviation from linearity occurs at these levels). From Fig. 3(c), the mean suppression of $n \times 2$ products of both mixers is very similar and with $P_R = 0$ dBm it is -39 dBc for the WM mixer and -37.5 dBc for the AVANTEK mixer.

Fig. 3(d) shows the measured results of $n \times 3$ products as functions of P_R with $P_L = 15$ dBm. The suppression of $n \times 3$ products is a linear function of P_R with the slope of 2, provided $P_R < 0$ dBm. (Power measurement of a product as low as the noise level causes error in the measurement; therefore deviation from linearity occurs at these levels). From Fig. 3(d), the mean suppression of $n \times 2$ products of both mixers is very similar and with $P_R = 0$ dBm is -57 dBc for the WM mixer and -54.5 dBc for the AVANTEK mixer. Note that in both mixers (odd)$\times$(odd) products are the highest, due to the balance effect.

A study of the measured results in Fig. 3(a)–(d) shows the linear relationship between P_R and the spurious-response suppression. This phenomenon can be very useful, because one can use it in order to control mixer products. The order m determines spurious-response suppression in both mixers as well as in other mixers that were measured in a similar way. It has been shown that, when m is larger, suppression improves significantly. Thus the input power and the order m have great influence on spurious-response power. The influence of mixer balance was also shown and one can see that, generally, the (odd) $\times$(odd) products are the highest in the group. From Fig. 3(a)–(d), the order n itself has no consistent influence on product suppression. Additional measurements have shown that variations in local oscillator power do not affect product suppression in any consistent manner.

V. Discussion

Initially it seemed possible that a precise prediction of spurious-response suppression for a double-balanced mixer could be obtained if the unknown parameters V_L, V_R, and A_{nm} in (25) could be determined. It seemed that by measuring the power of eight spurious-response products at a particular input power it should be possible to solve the resulting eight nonlinear equations for the unknown parameters. Extensive attempts to solve the resulting systems of nonlinear equations did not lead to a solution. It appears that the problem has no single solution but many. Thus the author concluded that a determination of the parameters V_L, V_R, and A_{nm} is not a realistic goal and thus it is not possible to precisely predict spurious-response suppression using (25). However, the use of (25) in order to understand the influence of the input power, P_R, and the order m can be very enlightening. With P_R and P_L set, we can determine the influence of the order m on spurious-response suppression. From (25) and the measured data in Fig. 3(a)–(d), we may conclude that m determines product suppression and that when m is larger suppression improves. Dividing the products into groups: $n \times 0$, $n \times 1$, $n \times 2$, $n \times 3$, etc. (as was done in Fig. 3(a)–(d)), we may conclude that each group has its own characteristic suppression and the results are consistent for each mixer (as well as for others that were measured). Taking the mean suppression in each group (i.e., the average over the order n to neglect the influence of A_{nm}/A_{11} or rather treat A_{nm}/A_{11} as independent of n), we find very similar results for both the AVANTEK and the WM mixers. It is necessary to evaluate V_R in order to examine quantitative agreement between these mean results and (25). A very simple way to do this is to use (25) with two of these means at different m orders and to neglect the influence of A_{nm}/A_{11}.

Applying this calculation to the groups $n \times 0$ and $n \times 1$ using the mean values -10.5 dBc and -23 dBc respectively (as were found in the measurements with $P_R = 0$ dBm) for the AVANTEK mixer, one obtains $aV_R/2 \approx 0.237$. Using this value, the calculated mean suppression of $n \times 2$ products should be -41.5 dBc, while the mean of the measured products is -37.5 dBc; the calculated mean suppression of $n \times 3$ products should be -51 dBc, while the mean of the measured products is -54.5 dBc. This examination can be applied to other mixers in a similar way, showing that the influence of m is approximately given by $1/m!(aV_R/2)^{m-1}$.

The influence of the input power P_R on spurious-response suppression is, from (26), defined by the $(m-1)$ rule. This is verified by measurements shown in Fig. 3(a)–(d). One may write

$$S_{nm}(\mathrm{dBc}) = (m-1)P_R(\mathrm{dBm}) - E_{nm}(\mathrm{dBm}) \qquad (27)$$

where E_{nm} is a constant which is a function of P_L and the mixer balance. Thus when P_L is fixed, one can find E_{nm} for a specific product by a single measurement and then determine S_{nm} of this product for any P_R (but sufficiently low relative to P_L). The term A_{nm}/A_{11} in (25) is a function of P_L and the mixer balance. The inherent suppression of even products in double-balanced mixers has been explained in the analysis and the measured results presented in Fig. 3(b) and (d), showing close agreement. Thus low-order (odd)$\times$(odd) products in the group are the least suppressed when the mixer is well balanced. The influence of the local oscillator power $P_{L'}$ on spurious-response suppression according to (25) does not obey any simple rule, and is a function of the mixer balance. Thus, changing the local oscillator power level is not the proper way to control the spurious-response suppression.

IV. Summary

The resistive-diode exponential characteristic was used to characterize spurious-response suppression of a single-diode mixer. A simple new analysis was presented based on the assumption of a sinusoidal local oscillator voltage and the approximation $V_L \gg V_R$, which does not require the use of a computer.

The analysis was applied to double-balanced mixers, considering the inherent cancellation effect in these mixers in the case of nonideal balance. Measurements of two different microwave mixers were carried out verifying the following conclusions predicted by the analysis: 1) a direct relationship exists between the order of a product and its suppression and 2) a linear relationship exists between the RF input power and the suppression. The first conclusion permits approximate prediction of the suppression using Fig. 3(a)–(d). The second conclusion permits a prediction of the suppression at any RF power level from a measurement taken at a single level.

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