The Cause of Conversion Nulls for Single-Diode Harmonic Mixers

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***Abstract*—Recent experimental measurements have found that for a single-diode harmonic mixer there exists a dc bias level for which the conversion to the IF goes to zero, with reasonable efficiency on either side of this null. This letter shows that these nulls are caused by competition between the different mixing paths through which a signal can be converted from the RF to the IF. A simple small-signal analysis is used to give a clear insight into the mixing behavior behind the nulls.**

***Index Terms*—Harmonic mixer, small signal analysis.**

I. Introduction

IT HAS been observed experimentally by several groups that for a single-diode second harmonic mixer (i.e., a mixer with LO pump at approximately half the RF frequency) there exists a dc bias level for which the conversion efficiency goes to zero, with reasonable efficiency on either side of this null [1], [2]. However, while pointing out the existence of these nulls, these researchers were not able to determine the root cause of this phenomenon. This letter examines the source of these conversion nulls, and shows that they are caused by competition between the different mixing paths through which a signal can be converted from the RF to the IF. A simplified small-signal analysis is used to give a clear insight into the mixing behavior behind the nulls.

II. Harmonic Balance Analysis for Harmonic Mixer

In order to understand the phenomenon, we first used a standard harmonic balance technique [3] to analyze the conversion efficiency of a single-diode harmonic mixer as a function of dc bias. Using measured diode I–V characteristics and estimates of the embedding impedances, it was found that the analysis predicted a conversion null similar to that seen in the measurements. In addition, the harmonic balance analysis suggested that in general for an Nth harmonic mixer with LO pumping at (approximately) $1/N$ of the RF frequency there exist $N-1$ conversion nulls. Additional harmonic balance analyzes with both the diode series resistance and junction capacitance set to zero showed that this phenomenon occurred with only a nonlinear resistance present.

Manuscript received August 17, 1999; revised October 4, 1999. This work was supported by the U.S. Army National Ground Intelligence Center under Contract DAHC90-96-C-0010 and by NASA-GSFC Grant NAG5-6507.

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Publisher Item Identifier S 1051-8207(99)10322-2.

Now, consider the case of second harmonic mixing. Two possible paths by which the RF power can be converted to the IF are: 1) the "standard" path, where RF power $(\omega_{RF} = 2\omega_{LO} + \omega_{IF})$ mixes with up-converted LO power at $2\omega_{LO}$, generating power at ω_{IF}, and 2) an alternate two-step path, where RF power mixes first with the original LO signal at ω_{LO}, generating currents at $\omega_{LO} + \omega_{IF}$, which then re-mix with the LO signal at ω_{LO}, thus generating power at ω_{IF}.

While the two-step path may seem of secondary importance, using the rule of thumb given by Torrey and Whitmer [4] (i.e., that the order of magnitude for a given mixing product is G^n where n indicates the mixing of a signal with $n\omega_{LO}$ and G is the conversion gain from $\omega_{LO} + \omega_{IF}$ to ω_{IF}), we see that both paths will convert to ω_{IF} with efficiency of order G^2. Thus, it is reasonable that under certain conditions these two paths can cancel at the IF.

One simple test of this multipath theory is to run harmonic balance simulations with the frequency $\omega_{LO} + \omega_{IF}$ short-circuited. Such simulations were performed, and they indicated that for an Nth harmonic mixer, shorting the frequency $\omega_{LO} + \omega_{IF}$ reduces the number of nulls to $N-2$ (thus there will be no null for a second harmonic mixer). A simulation with the lower sideband frequency $\omega_{LO} - \omega_{IF}$ short-circuited did not reduce the number of nulls.

III. Small-Signal Analysis for Second Harmonic Mixing

In order to show how the presence of multiple mixing paths can lead to IF cancellation, we can use small-signal mixer analysis to analyze the various mixing paths. The following analysis uses two simplifying assumptions: 1) that the sidebands for the third and higher LO harmonics are short-circuited, and 2) that the lower sideband frequencies ω_{-2} and ω_{-1} (where $\omega_m = \omega_{IF} + m\omega_{LO}$, following the notation of [5]) are also short-circuited. Shorting the lower sidebands does not affect the presence of the dips since the two paths are through the upper sidebands.

Using these assumptions the small signal problem reduces to

$$\begin{bmatrix} I_0' \\ I_1' \\ I_2' \end{bmatrix} = \begin{bmatrix} Y_{00}' & Y_{01}' & Y_{02}' \\ Y_{10}' & Y_{11}' & Y_{12}' \\ Y_{20}' & Y_{21}' & Y_{22}' \end{bmatrix} \begin{bmatrix} V_0' \\ V_1' \\ V_2' \end{bmatrix}. \quad (1)$$

Note that we are dealing with the augmented matrix, and are thus assuming that the embedding impedances at the remaining frequencies have already been included in the matrix (see [5]). Now, if we let $I_1' = 0$ (thus assuming $\omega_{LO} + \omega_{IF}$ is terminated by the embedding impedance only), then we can solve the second row for V_1' and eliminate it in (1), yielding a new set of equations which link the IF and RF currents and voltages

$$\begin{bmatrix} I_0' \\ I_2' \end{bmatrix} = \begin{bmatrix} Y_{00}'' & Y_{02}'' \\ Y_{20}'' & Y_{22}'' \end{bmatrix} \begin{bmatrix} V_0' \\ V_2' \end{bmatrix}. \tag{2}$$

The coefficient of interest, Y_{20}'', can be shown to be given by

$$Y_{20}'' = Y_{20}' - \frac{Y_{21}' Y_{10}'}{Y_{11}'}. \tag{3}$$

This coefficient links the RF voltage to the IF current, and if Y_{20}'' goes to zero then the conversion to the IF will also go to zero. Examining this equation, we see that the first term represents the "standard" mixing path described above, and the second term represents the alternative mixing path. If the admittances for these two mixing products are of the same magnitude and phase, then they will cancel, and there will be no currents at the IF. This therefore provides the explanation for the conversion nulls.

IV. NUMERICAL EXAMPLE

Let us now examine these mixer conversion coefficients for a concrete example. We have performed a simple large-signal/small-signal analysis of an ideal exponential Schottky diode. For forward biased operation $(v \gg V_0)$ the diode conductance can be written

$$g_j(v) = \frac{I_{sat}}{V_0} e^{(v/V_0)} \tag{4}$$

where I_{sat} is the saturation current and V_0 is given by

$$V_0 = \frac{\eta k T}{q} \tag{5}$$

where q is the electron charge, η is the ideality factor, and k is Boltzmann's constant [6]. The series resistance was assumed to be zero, and the dc and LO voltages were applied directly across the junction. For an applied voltage $v(t)$ of the form

$$v(t) = V_{DC} + V_{LO}\cos(\omega_p t) \tag{6}$$

the diode conductance waveform can then be expanded in a Fourier series

$$g(t) = \sum_{n=-\infty}^{\infty} G_n e^{-jn\omega_p t} \tag{7}$$

where the Fourier components G_n can be shown to be given by

$$G_n = \frac{I_{sat}}{V_0} e^{V_{DC}/V_0} I_n\left(\frac{V_{LO}}{V_0}\right) \tag{8}$$

where $I_n(z)$ is the modified Bessel function of the first kind of order n. One thing to note at this point is that the Fourier components of $g(t)$ vary exponentially with V_{DC}, and thus there will be no nulls in these spectral components as V_{DC} is varied. The conversion nulls are therefore not caused by nulls in the spectrum of $g(t)$.

Using this conductance spectrum we can then perform a small-signal analysis to determine the conversion loss. For our numerical example the RF, IF, and LO + IF embedding impedances were set to 50 ω, and all other frequencies were

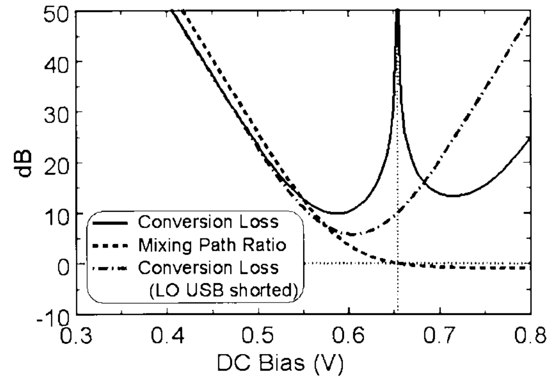

Fig. 1. Conversion loss versus bias for a nonlinear resistance compared with the ratio of standard versus alternate mixing path conductances.

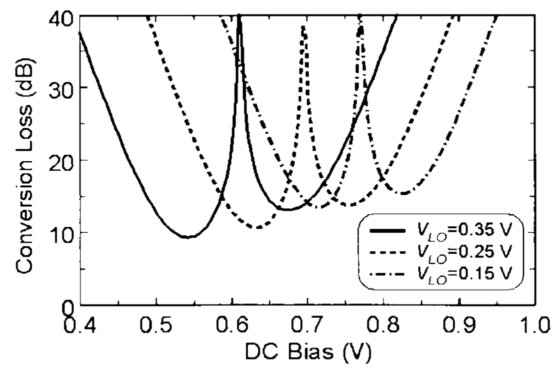

Fig. 2. Conversion loss versus bias for several different values of V_{LO}.

assumed shorted, as required by the analysis used to derive Y_{20}''. The diode parameters for a University of Virginia SC1T5 planar Schottky diode were used (anode diameter 1.2 μm, $I_{sat} = 3e$-16 A, $\eta = 1.17$). The simulation is frequency independent since the element is purely resistive.

As shown in Fig. 1 for a V_{LO} of 0.3 V, this analysis predicts a conversion loss dip at a dc voltage just above 0.65 V. In addition, Fig. 1 shows a graph of ρ, defined as the ratio of path 1 to path 2, given by

$$\rho = \frac{Y_{20}'}{\left(\frac{Y_{21}' Y_{10}'}{Y_{11}'}\right)}. \tag{9}$$

Using (3) and (8) it can be shown that this ratio is given by

$$\rho = \frac{I_2\left(\frac{V_{LO}}{V_0}\right)}{I_1\left(\frac{V_{LO}}{V_0}\right)^2}\left(I_0\left(\frac{V_{LO}}{V_0}\right) + Y_{e1}\frac{V_0}{I_{sat}}e^{-V_{DC}/V_0}\right) \tag{10}$$

where Y_{e1} is the embedding admittance at $\omega_{LO} + \omega_{IF}$. When ρ is greater than one, the standard path is dominant, and when less than one the alternate two-step path is dominant, and at the point where (is equal to one the conversion loss is infinite. The final curve in Fig. 1 shows the conversion loss when the upper-sideband frequency of the LO (i.e., $\omega_{LO} + \omega_{IF}$) is short-circuited, showing that the removal of the alternate mixing path has eliminated the conversion null.

Fig. 2 shows the effect of the LO drive level on the conversion loss. Increasing V_{LO} is seen to decrease the bias voltage at which the null occurs, while improving the conversion efficiency as expected. The basic shape of the conversion loss curve remains roughly the same for the different LO levels.

V. Conclusions

We have explained the source of the conversion nulls in single diode harmonic mixers. This analysis points out the importance of considering the various mixing paths when thinking about a given mixer's conversion loss. This is particularly important for single-diode harmonic mixers, but is also an issue for balanced mixers, since competition between different mixing paths can have a significant effect on the system performance.

References

[1] R. Titz, "Untersuchung von GaAs-Schottky-Dioden mit Submillimeter-Lasern," dissertation, Univ. Bonn, Germany, 1991.

[2] D. W. Porterfield, "Subharmonically pumped mixers at submillimeter wavelengths," M.S. thesis, Univ. Virginia, Charlottesville, 1994.

[3] P. H. Siegel and A. R. Kerr, "Computer analysis of microwave and millimeter-wave mixer," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 275–276, Mar. 1980.

[4] H. C. Torrey and C. A. Whitmer, *Crystal Rectifiers* (M.I.T. Radiation Lab. Series 15). New York: McGraw-Hill, 1948.

[5] D. N. Held and A. R. Kerr, "Conversion loss and noise of microwave and millimeter-wave mixers: Part 1—Theory," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, pp. 49–55, Feb. 1978.

[6] S. A. Maas, *Nonlinear Microwave Circuits*. Norwood, MA: Artech House, 1988.