IMAGE CONVERSION EFFECTS IN DIODE MIXERS

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Abstract

A time-domain technique is presented for the analysis of mixers. Three simple circuit models using "ideal diodes" have been analyzed exactly, yielding values for their optimum impedance conditions and expressions for the conversion coefficients for all small-signal first-order conversion products. Some new physical insights are obtained. Without image rejection, 3.92 dB conversion loss is the minimum for an untuned mixer, 3.36 dB with single-stub tuning, and 3.0 dB with resonator tuning. For the optimum bias level and IF impedance, no image signal is generated in any of these cases. With an image band-stop filter, lower conversion loss is predicted when the impedances are changed, but, the improvement predicted is small unless the conversion loss without the image filter can approach 3.0 dB.

I. Simple Circuit Models and Method of Approach

Figures 1, 2 and 3 show three simple single-diode mixer mounts, together with their equivalent circuits. In Figure 1, no tuning is used. The diode is placed at the end of a TEM line of impedance R_O. A blocking capacitor prevents IF and DC flow in the RF line. An RF choke extracts the DC and IF. The RF source is assumed to be resistive, of impedance R_O, with two voltage generators, one for the LO and one for the signal. The rectified output is fed to an IF load resistance and an optional "battery" is added for bias control (in practice, biasing is usually provided resistively with different IF and DC impedances). It is assumed that the diode is "ideal", with zero impedance in forward bias and infinite in reverse, and with no parasitic reactance or resistance.

The signal voltage is assumed to be much smaller than that of the LO and the IF is assumed to be a very small fraction of the signal frequency. The blocking capacitor is assumed to have infinite IF reactance and zero RF reactance while the choke has infinite RF reactance and zero IF reactance. The sum of the signal plus LO voltages is approximated as a cosine wave which is slowly modulated in amplitude and phase, based upon geometrical analysis of the vector diagram.

$$V_p \cos \omega_p t + V_{p\pm s} \cos(\omega_p t \pm \omega_s t + \psi_{p\pm s})$$

$$\simeq (V_p + V_{p\pm s} \cos \varphi) \cos \left(\omega_p t + \frac{V_{p\pm s}}{V_p} \sin \varphi\right) \qquad (1)$$

where

$$\varphi = \pm\omega_s t + \psi_{p\pm s} \qquad (2)$$

Here the subscript s refers to the IF and $p\pm s$ to the signal just above or just below the LO frequency ω_p. In Eq. (1) φ is assumed to vary so slowly that it may be assumed constant for any few cycles of ω_p, so that Eq. (1) acts as a true sine wave, with its amplitude and phase determined by the parameter φ. Later, φ is allowed to vary with time according to Eq. (2) and this "modulates" the rectified and RF currents.

In the analysis, waveforms are determined as analytic expressions for the periods of forward and reverse bias. First, by assuming φ is a constant parameter, expressions for the rectified current and the RF currents are obtained as a Fourier series whose coefficients are dependent upon φ. When φ is allowed to vary according to Eq. (2), the DC component and each harmonic of the LO frequency becomes amplitude and/or phase modulated. The IF current is the variation in the DC component of the series and the RF modulation products are the modulation sidebands around the pump frequency and its harmonics. The optimum conduction angle, IF impedance, bias level, and other parameters are determined to minimize the conversion loss.

Similar methods were used to analyze the circuits of Figures 2 and 3 also. For Figure 2, the TEM stub beyond the diode acts as a short circuit for all even harmonics. In Figure 3, the diode is assumed to be shunted across an antiresonant L-C tank at the terminus of the line. Here, it is assumed that the capacitance is sufficiently large that it acts as a short-circuit at the diode for all higher harmonic frequencies. The resonance is assumed to be sufficiently broad to include the LO, signal and image frequencies.

II. Analytic Results for the Single-diode Circuits

The results of the analyses for the three illustrated circuits are presented in Table I. The parameters here are chosen for minimum conversion loss. These results are, for the most part, not surprising, corresponding qualitatively if not quantitatively to many previously published theoretical results. To the author, however, the total lack of image response for each case was unexpected. It should be noted, however, that an image response will appear if the IF impedance is not optimally chosen. (In an experimental test of a conventional balanced mixer, image generation was found to vanish for the optimum IF impedance.) No improvement can be obtained by image rejection methods unless the impedance levels are changed as discussed in Section V. An interesting paradox exists in connection with the device of Figure 3. Under the assumptions made, the signal energy is entirely absorbed, the LO power is converted to DC with 100% efficiency, there are no higher order modulation products, and there are no internal losses, yet only 50% of the signal power is converted to IF. For this case it is postulated that the "lost" energy is converted to DC as a second-order increase in the rectified current.

	UNTUNED	STUB	RESONANT
Conduction Angle	180^o	134^o	$\rightarrow 0^o$
IF Impedance	R_o	$1.35\ R_o$	$2\ R_o$
Total Bias Voltage V_r	$.90\sqrt{P_{LO}R_o}$	$1.115\sqrt{P_{LO}R_o}$	$1.414\sqrt{P_{LO}R_o}$
DC Current	$.90\sqrt{P_{LO}/R_o}$	$.83\sqrt{P_{LO}/R_o}$	$.7071\sqrt{P_{LO}/R_o}$
Signal Return Loss	∞	31.4 dB	∞
LO Return Loss	∞	31.4 dB	∞
Image Conversion Loss	∞	∞	∞
Down-Conversion Loss	3.92 dB	3.36 dB	3.0 dB
Up-Conversion Loss	3.92 dB	3.36 dB	3.0 dB

Table I - Optimum Parameters for 3 Simple Ideal Mixers

III. The Scattering Matrix

Most previous mixer theories have made use of impedance or admittance matrices, applicable to the diode-junction. These are infinite matrices which can be validly reduced to manageable size only by assuming zero or infinite circuit impedance at all neglected frequencies; an impractical situation. The theory here can be used to determine the elements of a scattering matrix for the complete circuit, which is also infinite. Such a matrix can be validly reduced by omitting any frequency for which the external circuit can be assumed "matched" in impedance. For the signal, IF, and image frequencies, a three-frequency scattering matrix for the circuit of Figure 1 and Table I is given in Eq. (3) where the IF reference impedance is that which matches the internal IF impedance of the mount. It is assumed that the LO, which is not included, drives the diode in an even function with respect to time (as $\cos \omega_p t$).

	α^*_{p-s}	α_s	α_{p+s}	
β^*_{p-s}	0	.636	0	
β_s	.636	0	.636	(3)
β_{p+s}	0	.636	0	

Here the α's are input wave "voltage" quantities and the β's are output waves, with values normalized to the square-root of the powers involved.

IV. An Equivalent Circuit

For the cases studied, an equivalent circuit for a single-diode mixer is shown in Figure 4. This is shown as a hybrid transformer or "magic tee". The common "even" port represents the IF terminals and the "odd" port is an internal load. The RF ports are terminals for the upper and lower sidebands. An attenuator is shown in each RF port. .9 dB for Figure 1, .36 dB for Figure 2, and 0 dB for Figure 3. This accounts for losses to higher order mixing products (and other losses in non-ideal mixers). A "conjugator" is shown in the lower-sideband arm. This is an imaginary device which inverts the spectrum and phases. The scattering parameters of this circuit correspond to Eq. (3).

With a single RF input at one RF line, the wave is first attenuated (.9 dB for Figure 1), then equally divided between the internal load and the IF. With a single input at IF, no energy is lost to this load, and the energy is divided equally between the two sidebands, then attenuated .9 dB. With two equal sideband inputs, synchronized and phased with respect to the LO to produce AM at the diode, the waves are attenuated .9 dB and then fully converted to IF with only .9 dB net power loss. With two RF inputs so phased as to give phase-modulation at the diode, no energy is converted to IF and all is absorbed.

V. Filter-type Image Rejection

Using a scattering matrix of the form of Eq. (3), the effects of adding a band-stop filter for the image frequency have been analyzed. Lower conversion loss is obtainable by changing the IF impedance and setting the image impedance for infinite external reflection. For an open-circuit image, Figure 5 shows how the conversion loss can be reduced in this way, as a function of the IF impedance. The four curves are for different values of the minimum conversion loss when the image filter is omitted. It is seen that little improvement is available unless the normal conversion loss can be made low, approaching 3 dB. Also shown on Figure 5 are the modified values of the input signal impedance which results from this change.

VI. Multiple Diode Circuits

Ordinary balanced mixers use two circuits, such as in Figures 1, 2 or 3; combined with a hybrid coupler, magic tee or equivalent. For such circuits, the limiting conversion loss is the same as with a single-diode circuit.

Various forms of dual-balanced "image-cancelling" mixers using multiple diodes, with LO excitation in two or four phases, are well known. In at least two cases, low conversion loss has been reported.[1,2] Preliminary analysis, based upon the methods of Section I, indicates that such multiple diode circuits are, indeed, capable of lower conversion losses than conventional mixers. This work is continuing and will be reported in the future.

VII. "Black Box" Mixer Characterization

A single-diode mixer mount, in practical hardware form, can be characterized by means of a "rectification characteristic" chart in the form of Figure 6. This is useful for cases where the IF is a small fraction of the LO frequency, yielding a graphical estimate of the conversion loss. (Figure 6 was theoretically determined for the case of Figure 1.) The method is related to the "incremental" method of Torrey and Whitmer.[3] To draw the chart, LO power only is fed to the mixer for several fixed values, chosen so that the square-root of the LO power is changed by constant increments corresponding to equal increments of RF voltage. For each LO level, the DC bias is varied and the DC current is plotted as shown. A "load line" can be drawn on the chart for any chosen IF impedance as shown, passing through the chosen operating point. According to Eq. (1) the effect of adding a small signal is equivalent to varying the RF voltage sinusoidally as amplitude modulation. Then, the "operating point" can be thought of as moving sinusoidally along the load line, around the zero-signal operating point. The variation in rectified current constitutes the IF signal.

It can be shown that the maximum conversion "gain" for any operating point is

$$\frac{P_{if}}{P_{rf}} = \frac{\left[\dfrac{\partial(i_r)}{\partial(\sqrt{P_{LO}})}\right]^2}{8\left[\dfrac{\partial i_r}{\partial V_r}\right]} \qquad (4)$$

The two partial derivatives are easily determined graphically from the chart for any operating point. The optimum IF impedance is $(\partial i_r/\partial V_r)^{-1}$.

References

1. D. Neuf, "A Quiet Mixer," Microwave Jnl., vol. 16, p. 24, May 1973.

2. O. Palamutcuoglu, J. G. Gardiner and D. P. Howson, "Image Cancelling Mixers at 2 GHz," Report 172, Univ. of Bradford (England), February 1974.

3. H. C. Torrey and C. A. Whitmer, "Crystal Rectifiers," M.I.T. Rad. Lab. Series, vol. 15, McGraw-Hill, pp. 213-214.

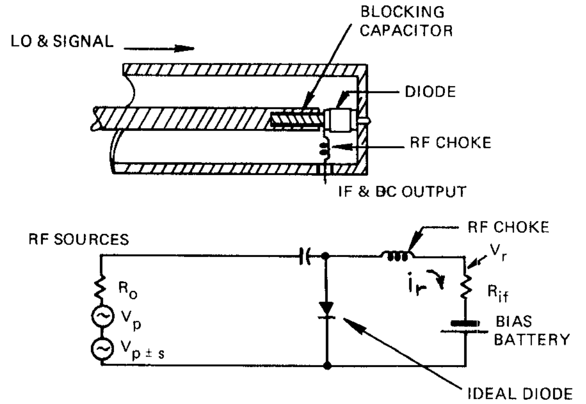

FIGURE 1 UNTUNED DIODE MOUNT AND CIRCUIT ANALYZED

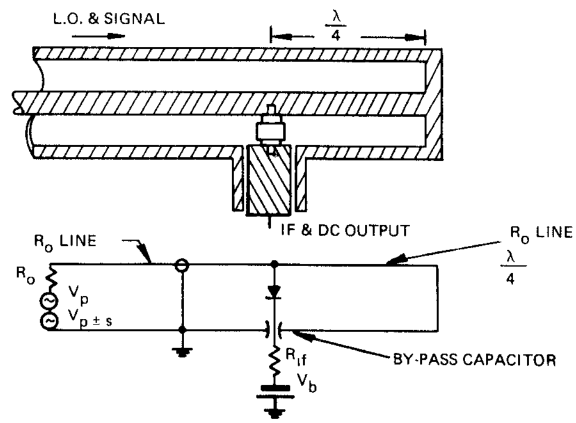

FIGURE 2 STUB-TUNED DIODE MOUNT AND CIRCUIT ANALYZED

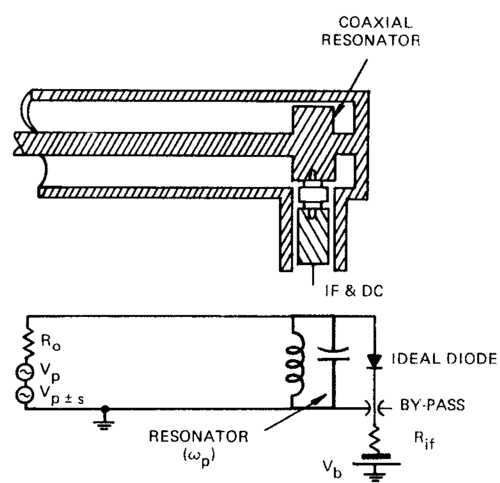

FIGURE 3 RESONATOR-TUNED MOUNT AND CIRCUIT ANALYZED

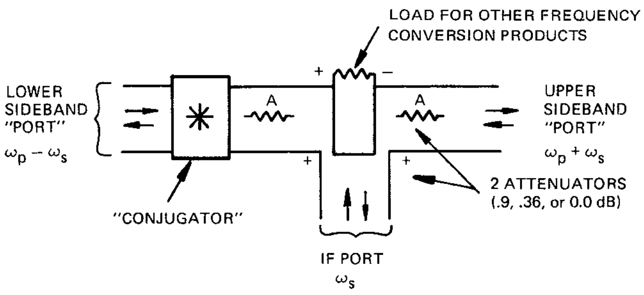

FIGURE 4 AN INTERESTING ANALOG TO THE SINGLE-DIODE SIMPLE MIXER, SHOWN AS A HYBRID JUNCTION

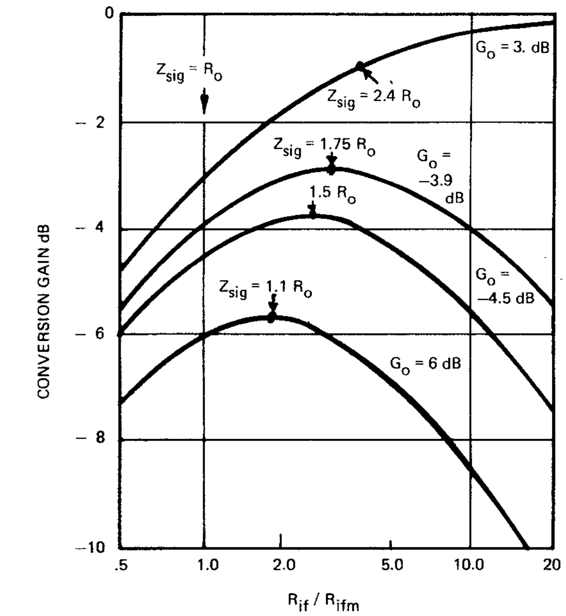

FIGURE 5 VARIATION OF CONVERSION GAIN WITH IF IMPEDANCE FOR OPEN-CIRCUITED IMAGE. G_o IS THE MAXIMUM GAIN FOR $R_{if} = R_{ifm}$. MODIFIED SIGNAL IMPEDANCE IS SHOWN FOR FOUR POINTS.

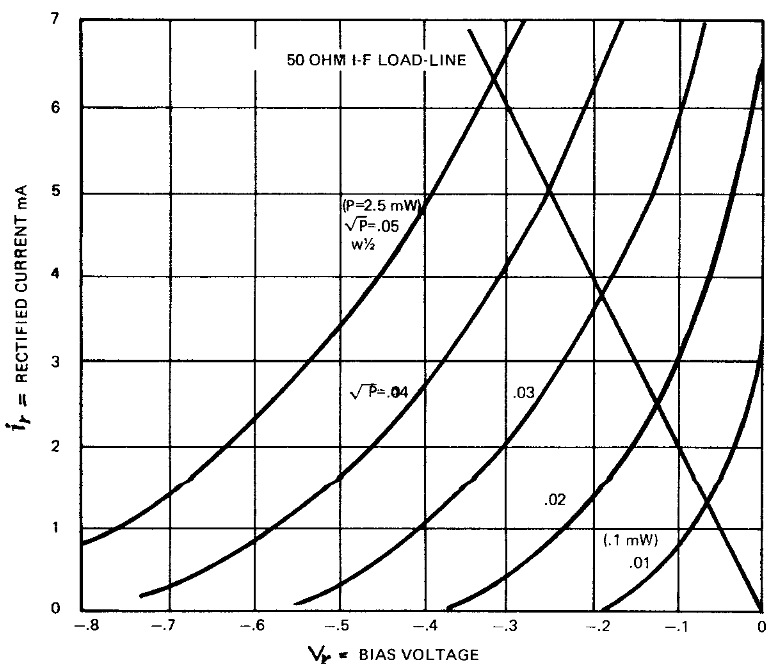

FIGURE 6 THEORETICAL "RECTIFICATION CHARACTERISTIC" FOR THE CIRCUIT OF FIGURE 1, R_o = 50 OHMS