IMAGE-OPTIMIZED, FREQUENCY-SCALABLE MIXERS FOR MILLIMETER-WAVE APPLICATIONS

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Summary

A unique IF measurement procedure for evaluating mixer performance and identifying optimum circuit boundary conditions is presented. The technique is applied to a scalable mm-wave single-sideband (image-sum enhanced) mixer design which provides 3.5 to 5 dB typical conversion loss from conventional, packaged devices.

I. Introduction

The purpose of this paper is threefold:

1. To identify an iterative synthesis procedure using straightforward IF-port measurements which specifies performance limits of single-sideband mixers and identifies associated optimum circuit boundary conditions (including the image termination).

2. To present a frequency-scalable, image-sum enhanced, single-sideband mixer design having unique features for achieving high performance with conventional packaged devices in the mm-wave frequency range.

3. To establish performance capabilities of the mixer for use in receivers (such as the NASA 30/20 program) and instrumentation (simplified mm-wave network analysis).

II. Mixer Performance Evaluation from IF-Port Dynamic-Q Circle Measurements

The performance of a single-sideband, image-enhanced mixer can be evaluated and optimized in a simple, direct manner by measurements made exclusively at the IF-port. This approach to mixer characterization has several significant advantages over other approaches:

1. Narrowband tuning elements, which may be lossy, are not required for matching at the signal and IF-ports to determine the minimum conversion loss.

2. Minimum conversion loss and the optimum IF impedance are easily determined so that optimum design of the IF matching network for broadband performance is possible.

3. Conventional network analysis at the IF is used to evaluate mixers having millimeter-wave signal frequencies.

4. Most important, boundary enhancement, including the image, of the mixer takes place through a straightforward iterative synthesis procedure.

The basic measurement procedure and evaluation technique is illustrated in Figures 1 and 2. As pumped, the mixer from signal to IF behaves as any linear time-invariant two-port network except for a change in frequency, and it can be represented by an intrinsic scattering matrix [S]. A variable reactance, such as an adjustable short circuit, terminates the signal port to provide a source reflection coefficient $\Gamma_s = e^{-j\vartheta}$, $0 <= \vartheta <= 2\pi$. Measurement of the reflection coefficient Γ_{out} at the IF-port for $0 <= \vartheta <= 2\pi$ then gives a circular locus as shown in Figure 1b in the Γ_{out}-plane. For a passive network, the Γ_{out}-circle is completely within the unit circle with the inside being the mapping of $|\Gamma_s| < 1$. The "size" and "location" of this circle specify the minimum coversion loss L_{min} and conjugate match IF impedance Z_{IF}.

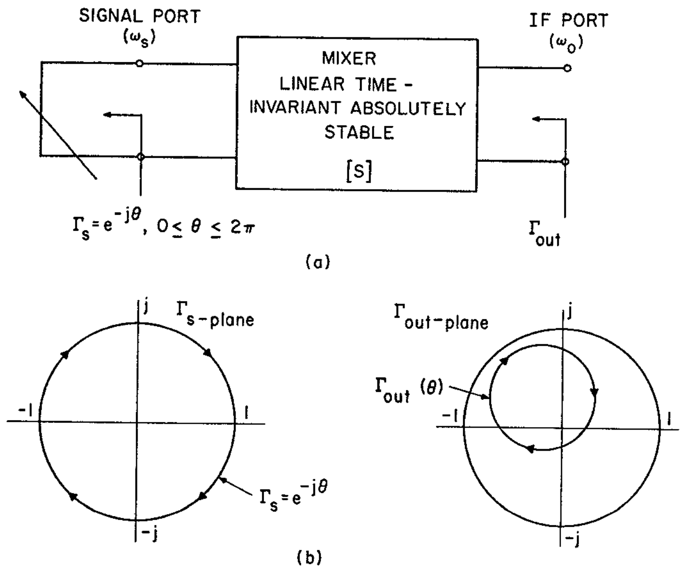

Fig 1. (a) Basic mixer characterization technique
(b) Γ_{out} locus as source reflection angle varies.

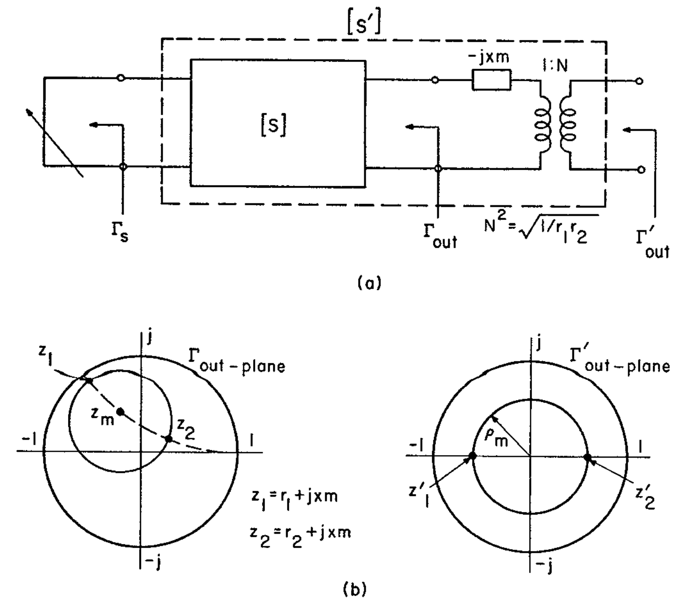

Fig 2. (a) Augmented mixer with IF matching network.
(b) Transformed Γ_{out} circle centered in Γ_{out}-plane.

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Values for $L_{\min}$ and Z_{IF} are deduced conceptually with the aid of Figure 2. A simple lossless transforming network can be identified which maps the Γ_{out} -circle into a circle centered at the origin of the Γ''_{out}-plane and having a radius ρ_m. The required network transforms the "matchpoint impedance" [1] Z_m to the origin of the Γ''_{out} -plane. For a mixer, the normalized value of Z_m is given by

$$z_m = \sqrt{r_1 r_2} + jx_m \tag{1}$$

where r_1 and r_2 are the normalized resistances at the perpendicular intersections of the Γ_{out} -circle and the unique constant reactance contour x_m as shown. The value of z_m represents the conjugate of the optimum normalized IF load impedance z_{IF} and $\frac{1}{\rho_m}$ is the value of minimum conversion loss $L_{\min}$, where

$$L_{\min} = \frac{1}{\rho_m} = \frac{\sqrt{r_2} + \sqrt{r_1}}{\sqrt{r_2} - \sqrt{r_1}} \tag{2}$$

The result of Eq(2) is easily shown by considering the S-parameters $[S']$ of the intrinsic mixer augmented by the lossless output network. Since the signal port normalization impedance Z_{n1} of the S-paramaters is arbitrary, it can be chosen to make $S'_{22} = 0$ (value of source impedance which makes $\Gamma''_{out} = 0$). If $S'_{22} = 0$, then $S'_{11} = 0$ in order to have the Γ''_{out} -circle in Figure 2 centered on the origin. Then,

$$\begin{aligned} \Gamma''_{out} &= S'_{21}S'_{12}\Gamma_s \\ \text{or} & \\ \rho_m &= |S'_{21}S'_{12}|. \end{aligned} \tag{3}$$

If the mixer network is magnitude reciprocal (valid for single diode resistive mixers) then $|S'_{12}| = |S'_{21}|$ and $\rho_m = |S'_{12}|^2$. Hence, the intrinsic mixer is simultaneously conjugate matched when driven from a source impedance of Z_{n1} and terminated in a normalized load impedance $Z_{IF} = Z_m{}^*(S'_{11} = 0,\ S'_{22} = 0)$, and therefore $L_{\min} = \frac{1}{\rho_m}$.

A single sideband mixer which has a means for adjusting the image termination can be image optimized easily using this technique. The image termination which gives the largest ρ_m value is the optimum. The Γ_{out}-circles are often referred to as dynamic Q-circles.

III. Mixer Circuit Design

Optimal use of the mixer evaluation procedure given in Section II requires a design with separate ports for the IF, signal, and local oscillator frequencies as well as a means for adjusting the image termination. The mixer design presented here evolved from this constraint, in addition to the fixed L.O. frequency specification of the NASA 30/20 program and the desire to make use of readily available, packaged mixer diodes.

A cross-sectional view of the mixer circuit is shown in Figure 3 and indicates several unique features which are explained below:

1. The local oscillator is coupled to the diode from waveguide using a unique coaxial filter design which provides transmission zeros at the image and signal frequencies and unity transmission at the L.O. frequency. Hence, *the L.O. is injected, while the signal and image are trapped near the diode*. The backshort in the L.O. waveguide is used to optimize the match, and the radial line trap in the coaxial line above the L.O. waveguide isolates the IF port.

2. A reduced-width signal waveguide is cutoff to the and image frequencies, thereby trapping this energy in the region near the diode. The length of signal guide provides at least 20 dB of one-way attenuation to the L.O., *thereby effectively isolating the L.O. from the signal port.*

3. The image is tuned using the adjustable backshort in the waveguide near the diode. This guide has a cutoff frequency below the image frequency. The length of this guide between the diode and the reduced-width signal guide is adjusted so that, at the L.O. frequency, the cutoff guide reactive termination reflects a short circuit at the plane of the diode. Since this guide is in parallel with the opposite, backshort-tuned section but in series with the diode, *tuning the backshort has no effect on the L.O. coupling to the diode.* Hence, the short effectively tunes the trapped image frequency.

4. The sum frequency is trapped by a shorted $\lambda/4$ coaxial line below the diode.

The initial parameters for the circuit were determined by computer aided design usign the circuit analysis routines of MARTHA [2] and a model for the waveguide to coaxial line transformer as given by Chang and Ebert [3] Radial line designs and the model for the H-plane junction of two waveguides were obtained from Marcuvitz [4] and programmed for use with MARTHA. The complete circuit model proved to be quite accurate in that the mixer performed nearly optimum at the specified frequencies.

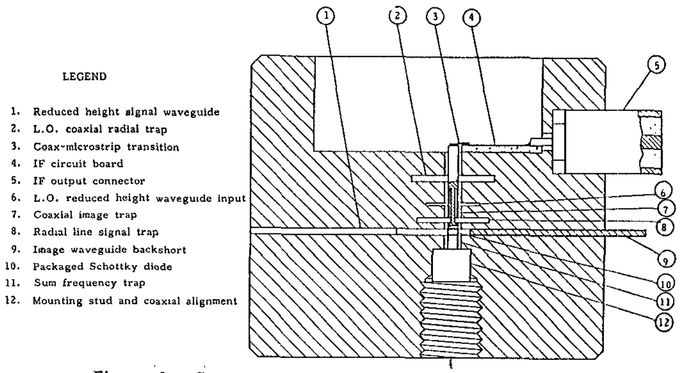

Figure 3. Cutaway section of mixer showing the various filters and I/O ports.

IV. Mixer Performance

Mixers of the form shown in Figure 3 have been made for signal frequencies of 22 GHz, 30 GHz, 35 GHz and 44 GHz. Shown in Table I are the parameters of these mixers and the minimum conversion loss achieved. The performance of the 35 GHz mixer is used for an example in this section.

TABLE 1

PARAMETERS AND PERFORMANCE OF SCALABLE MIXERS

Signal Band (GHz)	L.O. Freq. (GHz)	IF Band (GHz)	Dyn. Q Lmin (dB)	Max. IF VSWR In Band	6 dB Lmin B.W. (GHz)
33-39	29	4-10	4.5	5.5	2
27.5-30	25.2	2.3-4.8	3.2	5.9	>3
21-23	18	3-5	4.4	3.2	1
42-46	38	4-8	6.5	1.7	-

Dynamic Q-circles for this mixer were obtained by using a sliding Ka-band waveguide backshort terminating the signal port. Shown in Figure 4 are several circles obtained at an IF of 7 GHz for several image backshort positions. These data were taken with a manual network analyzer and the imperfections and loss associated with the waveguide sliding short is primarily responsible for the deviations from exact circular behavior. The dynamic-Q conversion loss and associated matchpoint impedance is shown for each of the circles.

Greater accuracy can be obtained by using a calibrated network analyzer and fitting many measured data points to a circle in the mean-square sense. Shown in Figure 5 are circles obtained in this way at IF frequencies from 4 GHz to 10 GHz at a fixed backshort position. The minimum conversion loss for this backshort position occurs at 7 GHz and is 4.6 dB. Measurements were referenced to the top of the coaxial line post on the diode, to indicate the frequency variation of the IF impedance.

Dynamic-Q conversion loss as a function of IF frequency for several image backshort positions is shown in Figure 6. Over a substantial range of positions, the loss between 6 and 7 GHz remains nearly constant, but the variation at the band edges is large.

The dynamic-Q conversion loss prediction was verified using a carefully calibrated power measurement for an IF of 7 GHz to be 5.2 dB +/- .2 dB. The actual down conversion loss will be larger than dynamic-Q predictions because the mixer is not truly reciprocal. Non-linear reactive effects will increase down conversion loss and reduce up conversion loss slightly (around .5 dB typically). Nevertheless, the simple evaluation procedure generally gives the optimal circuit conditions since minimizing dynamic-Q loss also minimizes down conversion loss.

The 30 GHz mixer design is an engineering development model for the receivers of the NASA 30/20 program. Designs at the other frequencies have been used as a single up/down converter allowing simplified mm-wave network analysis in a calibrated manner.

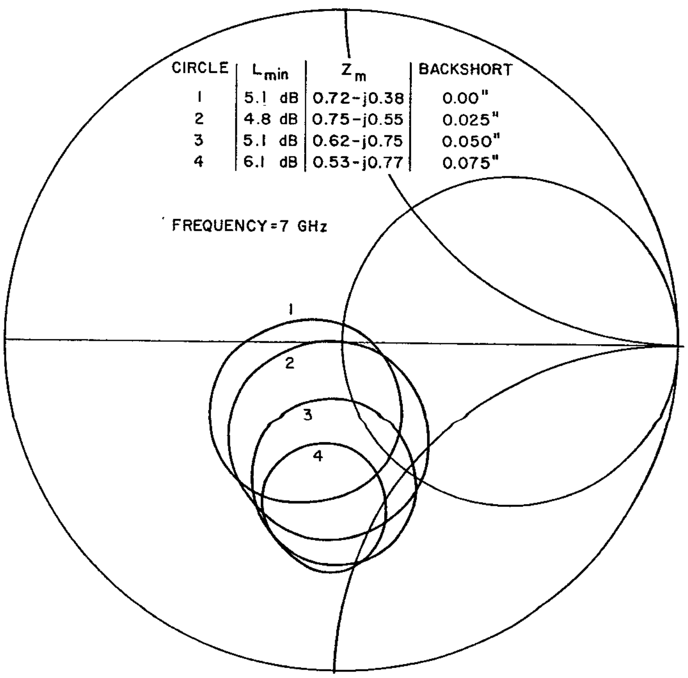

Fig 4. Dynamic-Q circles vs. image tuning for 35 GHz mixer.

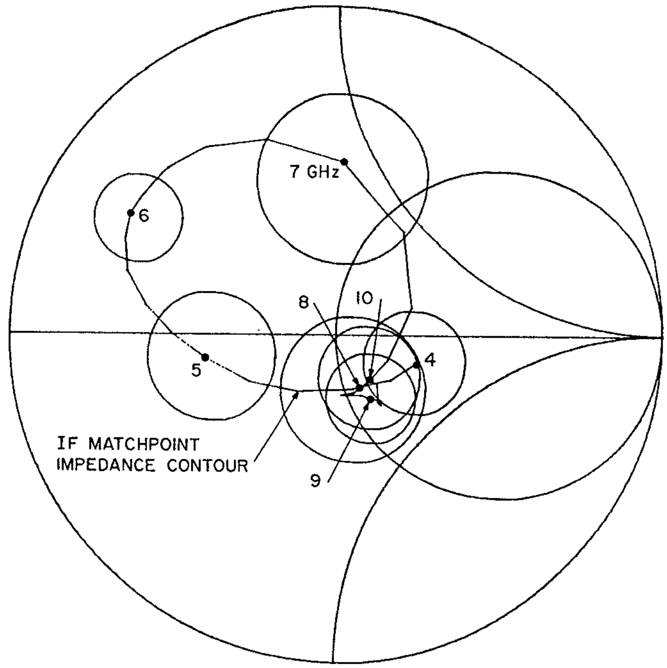

Fig 5. Dynamic Q-circles and IF matchpoint impedance over the 4-10 GHz IF band for a fixed image backshort.

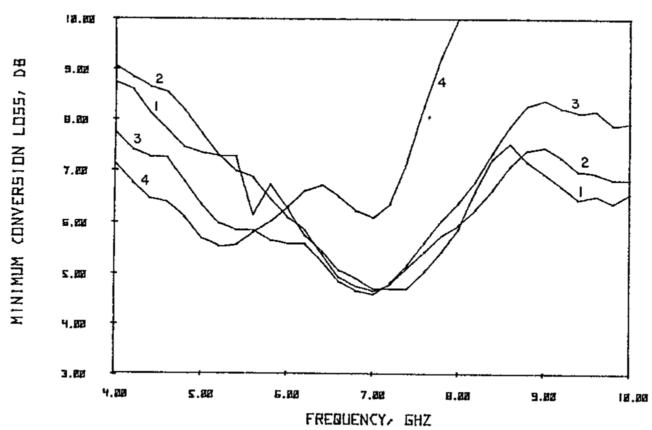

Fig 6. Dynamic-Q Conversion loss over the IF band for 4 image short positions.

Acknowledgement

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