A Novel General Approach for the Optimum Design of Microwave and Millimeter Wave Subharmonic Mixers

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***Abstract*— The design of subharmonic mixers is complicated and involves separation of signals and application of correct loading at the important idler frequencies. In this paper we present a novel general approach, which enables the designer to establish the optimum loading conditions for the different signals to get low conversion loss and good matching simultaneously. The method is demonstrated by a design example using a 30 GHz X2 subharmonic mixer. In this example it is shown that a nonoptimal design can yield conversion loss of up to 13.5 db, while an optimal design yields a conversion loss of 3.6 db.**

I. Introduction

SUBHARMONIC (SH) mixers are very useful at millimeter wave frequencies since low frequency low cost microwave sources can be used as the local oscillator (LO). Several authors have demonstrated good performance SH mixers at millimeter wave frequencies ([1]–[7]). In a SH mixer the mixing action is performed between the radio frequency (RF) or intermediate frequency (IF) signals and one of the harmonics of the LO. Thus, the nonlinear device (diode, metal semiconductor field effect transistor [MESFET], etc.) performs both mixing and frequency multiplication. Usually, the conversion loss of SH mixers is higher than fundamental mixers, however careful design can yield comparable performance. SH mixers are very sensitive to the loading of the nonlinear device at the various idler frequencies. At the LO, RF, and IF the device has a resistive load, but at all other frequencies generated in the nonlinear device it should be loaded by reactive load to avoid power loss, which increases the conversion loss of the mixer. However, this condition, while being necessary, is not sufficient, and the mixer performance is strongly dependent on the nature of the reactive load (short, open, capacitive or inductive). In this paper we present a generic method to determine the reactive loading of the various idler signals, which yields optimal performance of the SH mixer, namely, low conversion loss and good matching at the IF, LO, and RF ports.

II. The New Approach

A generic circuit of a Schottky diode based SH mixer is depicted in Fig. 1. The mixer incorporates an anti-parallel diode pair and three ideal two-port networks, one for each

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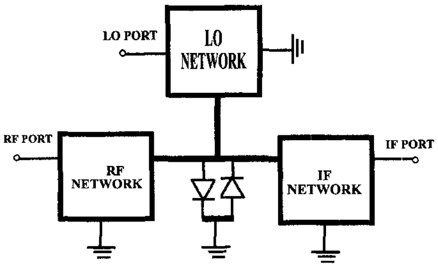

Fig. 1. A generic circuit of a subharmonic mixer.

output port (RF, LO, IF). The ideal two-port networks are presented by S parameter matrices as follows (port 1 of each network is adjacent to the diode pair):

1) *LO network*—at the LO frequency: $s_{11} = s_{22} = 0$, $s_{21} = s_{12} = 1$; at all other frequencies: $s_{11} = s_{22} = 1$, $s_{21} = s_{12} = 0$ (see explanation below);
2) *IF network*—at the IF frequency: $s_{11} = s_{22} = 0$, $s_{21} = s_{12} = 1$; at all other frequencies: $s_{11} = s_{22} = 1$, $s_{21} = s_{12} = 0$ (see explanation below);
3) *RF network*—at the RF frequency: $s_{11} = s_{22} = 0$, $s_{21} = s_{12} = 1$; at all other frequencies: $s_{21} = s_{12} = 0$, $|s_{11}| = s_{22} = 1$ (s_{11}—variable angle).

At the idler frequencies it is enough to vary the angle ofs_{11} of the RF network alone while keeping the angle of s_{11} of the other networks at zero (namely, open circuit), since all three networks are in parallel to the diode pair.

These ideal networks supply the necessary conditions for operation of the SH mixer. The optimization is performed on the angle of s_{11} of the RF network at the idler frequencies, which sets the reactive loading condition. For mixer operating under small signal conditions and utilizing an ideal anti-parallel diode pair (odd nonlinearity) the signals which are considered in the analysis (in addition to the LO) are of the form: $f = nf_{\text{LO}} \pm f_{\text{IF}}$, where n is an even number. Thus, the angle of s_{11} of the RF network at the above frequencies should be optimized. It is important to note that if the two diodes are not identical, the unbalancing causes circulating currents, and in that case all the harmonics should be considered. However, if one uses a monolithic diode pair, this effect is minimized. In this paper we did not consider the effect of unbalancing, however, this effect can be taken into account following the same approach as outlined here.

We have implemented the design approach by use of HARMONICA PC and LINMIC + /N, however any harmonic

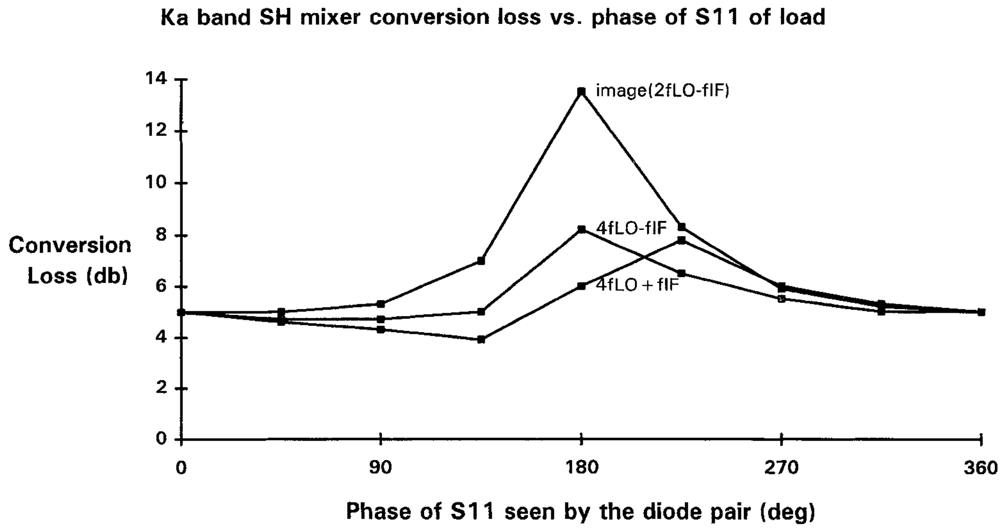

Fig. 2. Conversion loss versus phase angle of s_{11}.

balance simulator can be used. The following procedure ensures an optimal design of the SH mixer.

1) Enter the circuit in Fig. 1 into an harmonic balance simulator.
2) Represent the three ideal networks by ideal S parameter matrices as outlined above.
3) Simulate the circuit and calculate performance with the phase of s_{11} of the RF network at the idler frequencies varying over 0° to 360°.
4) Plot curves of the performance versus the phase angles.
5) Determine the optimum values of the phase angles and express the result as the optimum loading to be presented to the diodes at the various idlers.
6) Design a practical circuit, which approximates as best as possible the above requirements.
7) Simulate the practical circuit and verify the actual performance.

Usually it is very difficult to realize the optimum conditions simultaneously at all the idler frequencies in a practical circuit, however, the optimal conditions serve as design guidelines for the actual circuit. The dependence of the performance on the reactive loading at the idlers is quite strong, however, it is not a sharp optimum, and variations around the optimum do not have strong effect on the performance. This enables "near optimum" design even if there are deviations from optimum angle values in the practical circuit. In addition, the practical circuit has losses, which are not simulated in the generic design, however, these losses can be simulated for the actual circuit.

III. Design Example

We have implemented the above approach to aid in the design of a millimeter wave SH mixer operating as an up converter. The mixer is intended for use in the 30 GHz satellite communication band (27.5-31 GHz). The mixer converts the IF band of 4.5-8 GHz into the above mentioned RF band. The LO frequency is 11.5 GHz. The generic approach was implemented for the center frequencies, namely, an IF frequency of 6.25 GHz and an RF frequency of 29.25 GHz ($2f_{\mathrm{LO}}+f_{\mathrm{IF}}$). The harmonic balance analysis considers up to four LO harmonics, and thus there are three important idler signals: the image at 16.75 GHz ($2f_{\mathrm{LO}} - f_{\mathrm{IF}}$) and the two sidebands around the fourth LO harmonic-39.75 GHz ($4f_{\mathrm{LO}} - f_{\mathrm{FI}}$) and 52.25 GHz ($4f_{\mathrm{LO}} + f_{\mathrm{IF}}$). There are commercial anti-parallel diode pairs suitable for this application (MA/COM-MA40422, Philips CAY18M/AB). In the simulation we assumed a junction capacitance of 0.04 pF and a series resistance of 4Ω for each diode.

For this example, we followed the procedure outlined above. The results are depicted in Figs. 2 and 3. In Fig. 2 the conversion loss and in Fig. 3 the IF return loss are depicted versus the phase angle of s_{11} of the RF network (for each plot the phase angle at the other idlers is zero). From these curves it is obvious that the worst performance occurs for angles around 180°, namely, an effective short circuit, which maximizes the idlers currents via the diode pair (power loss). The largest sensitivity is at the image—the conversion loss varies from an optimum of 5 db at an angle of 0° to a maximum of 13.5 db at an angle of 180°. At the other idlers the sensitivity is smaller but still appreciable. The optimum performance is achieved for 0° at the image, 90° at $4f_{\mathrm{LO}} - f_{\mathrm{IF}}$ and 135° at $4f_{\mathrm{LO}} + f_{\mathrm{IF}}$. For these values the conversion loss is 3.6 db and the IF return loss is 22 db. These are extremely good results for this type of mixer, and we do not expect to achieve them in the practical circuit, however, this result can serve as a limit. In this particular example the RF and IF bandwidths are very large, and we do not expect to be able to design and build an optimal circuit over the entire bandwidth. Our approach was to design practical circuits, which present to the diode pair impedances as close as possible to the optimum derived for the ideal generic circuit.

The printed circuit pattern of the final design, which was implemented is depicted in Fig. 4. The circuit was printed on a 10 mil duroid substrate, and we used the Philips monolithic diode pair (CAY18M/AB). The simulated performance of the mixer using HARMONICA PC shows a conversion loss of 8 db+/−1 db over the entire frequency band (IF input in the

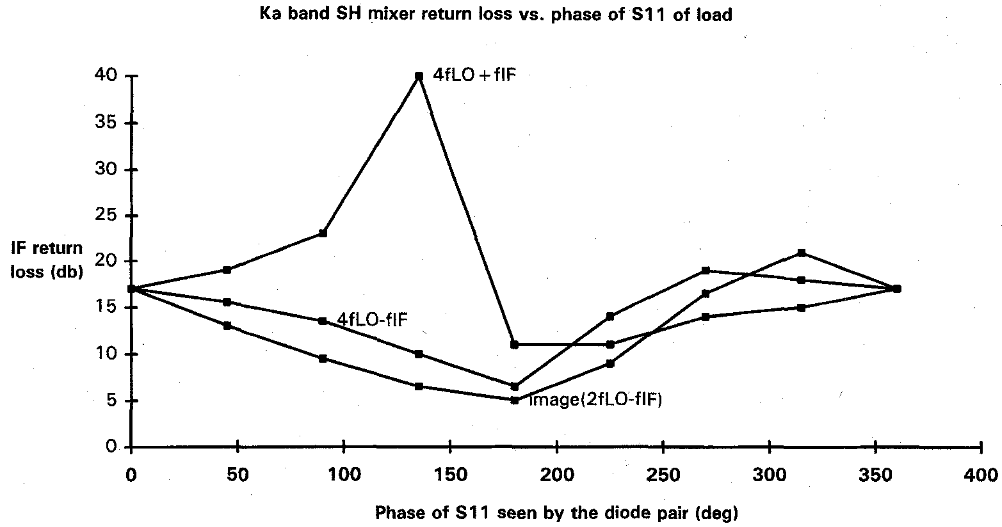

Fig. 3. IF return loss versus phase angle of s_{11}.

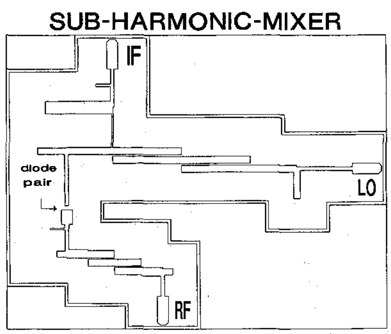

Fig. 4. Printed circuit pattern of the 30 GHz mixer.

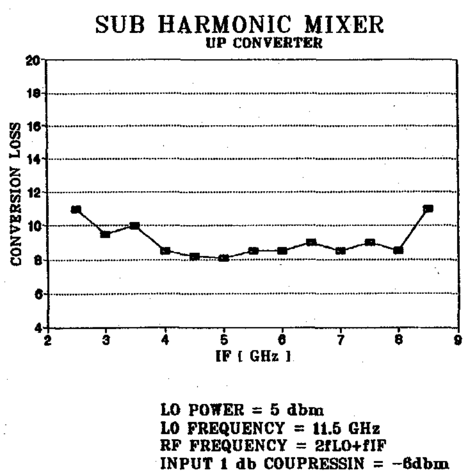

Fig. 5. Conversion loss of the 30 GHz mixer.

range 4.5-8 GHz). The deviation from the optimum predicted for the ideal network is due to: a) losses of the practical circuit (about 2.5 db); and b) deviations from the optimum loading over the bandwidth of the mixer. The measured performance of the mixer is depicted in Fig. 5. As can be seen the conversion loss over the IF band 4-8 GHz (corresponds to RF band 27-31 GHz) is 8-9 db, which is almost identical to the simulated results. The measured VSWR at all the ports in the entire frequency range is better than 2:1.

IV. Conclusion

In this paper we have presented a new generic approach, which allows a mixer designer to estimate the best achievable performance of the mixer as well as the loading conditions, which are necessary to achieve that performance. This can serve as both performance limit and design guideline. The new approach was demonstrated by a design example of a X2 subharmonic mixer operating as an upconverter in the 30 GHz satellite communications band.

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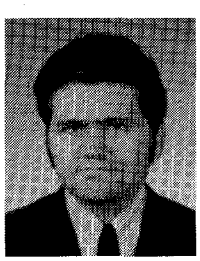

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