Analysis of Methods for Characterizing Frequency-Converting Devices

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***Abstract*— We propose a theoretical analysis of methods for characterizing devices with frequency conversion (vector mixer calibration methods). There are several methods for making such measurements, but their advantages and disadvantages have not been analyzed until now. This paper compares values of phase error and estimates of delay between three known vector mixer calibration methods. Analysis is made for the RF band. We use flow graphs and Mason theorem to calculate error limits of different methods.**

***Kywords*-frequency conversion; phase measurement; vector mixer calibration; RF mixer; group delay; phase**

I. INTRODUCTION

ALMOST all modern RF systems that have phase modulation networks implement heterodyne frequency conversion techniques. The main component of any frequency-converting device is its non-linear element, RF mixer that creates amplitude and phase distortions in the information signals that are converted by such mixer. It is impossible to estimate and disable these distortions if the phase shift and group delays of the frequency converting device are unknown. Therefore, the input RF signal of the mixer and its output IF signal have different frequencies, and it is impossible to compare phase of these signals any traditional way. A one-diode mixer brings in phase shift (error) to the IF signal that can be characterized by the widely known equivalent circuit of a semiconductor mixer that contains parallel connection of p-n barrier capacitance C_b and p-n active impedance r_g. The spilling active impedance R_s and the semiconductor volume inductance L_s are constants and do not depend on the current going through the diode. The impedance of the diode Z_n can be calculated using (1):

$$Z_n = \frac{r_g}{r_g^2\omega^2 C_b + 1} - j\frac{r_g{}^2\omega C_b}{r_g^2\omega^2 C_b + 1} \tag{1}$$

where $\omega = 2\pi f$ is the frequency of the signal that is going through the p-n. From the formula (1) it is possible to get analytical equation for the phase shift φ_0 that mixer's diode brings in the signal:

$$tg(\varphi_0) = \frac{\mathrm{Im}(Z_n)}{\mathrm{Re}(Z_n)} = \frac{-r_g^2\omega C_b}{r_g} = -2\pi f r_g C_b \tag{2}$$

The phase shift φ_0 dependence on the frequency (frequency response) can be calculated:

$$\varphi_0 = \arctan(-2\pi f r_g C_b) \tag{3}$$

From equations (2) and (3) it can be seen that the mixer's phase shift φ_0 is mainly defined by the barrier capacitance C_b that is extremely complex to estimate theoretically without substantial errors that can reach 200 %.

All these facts lead to a conclusion that it is much easier and incomparably accurate to characterize RF mixer phase shift and delay with instrumental methods that nowadays became basic for such measurements.

By the way, knowledge of RF mixer phase response makes it possible to calculate its complex transmission coefficient (magnitude and phase), that leads to the ability to characterize such mixer with S-matrix and introduce it as a 4-pole network with frequency conversion.

II. THE SUM AND DIFFERENCE METHOD

One of the earliest instrumental methods that allowed defining absolute phase shift of the RF frequency converters (mixers) was first introduced in USSR in 1986 [1] and is based on measuring the sum and difference of phase shifts of two mixers, where one is mixer under test and another is additional mixer. Structural diagrams of this method are shown in fig. 1.1 and 1.2. In fig 1.1 signals from the RF generator 1 with frequency f_1 through the tee 2 come to the mixers' 4 and 6 RF inputs. LO inputs of mixers 4 and 6 are powered by the signal with frequency f_2 that comes from the RF generator 3 through the tee 5. Inside mixers 4 and 6 these two RF signals are converted to the IF signals with low frequency $f_3 = f_1 - f_2$

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Then these two IF signals come to the inputs of the vector voltmeter 7, where their phase difference $\Delta\varphi = \varphi_1 - \varphi_2$ is measured. In this kind of measurements mixers are connected in parallel to each other. Then as shown in fig. 1.2 mixers 4 and 6 are connected in series with each other, so the connection of the generator 3 to their LO inputs stays untouched but their RF inputs are connected together. Signal from the IF generator 8 is divided

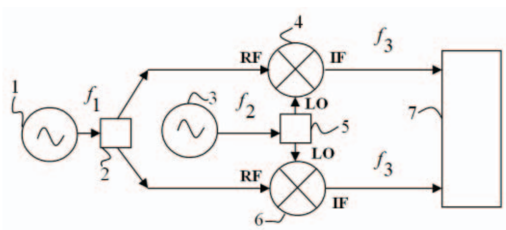

Fig. 1.1. Circuit of mixers in parallel

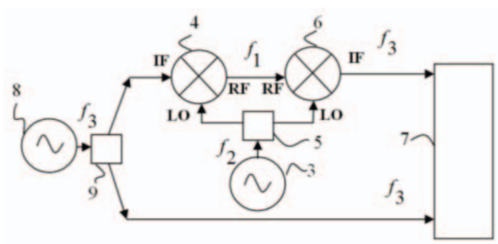

Fig. 1.2. Circuit of mixers in series

in the tee 9 and one part of this signal goes to the IF input of mixer 4 and another part goes to one of the vector voltmeter 7 inputs. Inside mixer 4 IF signal is converted to the RF signal with frequency $f_1 = f_3 + f_2$ which then comes to the RF input of mixer 6, where it is converted back to the IF signal with frequency $f_3 = f_1 - f_2$. Finally, after double conversion IF signal comes to one of the inputs of the vector voltmeter 7. As a result, vector voltmeter 7 registers phase shift sum of two mixers 4 and 6 $\Sigma\varphi = \varphi_1 + \varphi_2$. By solving the system (4)

$$\begin{cases} \Delta\varphi = \varphi_1 - \varphi_2 \\ \Sigma\varphi = \varphi_1 + \varphi_2 \end{cases} \tag{4}$$

we can find true (absolute) phase shift of any of the two mixers, for example:

$$\varphi_1 = \frac{\Sigma\varphi + \Delta\varphi}{2} \tag{5}$$

The advantage of this method is that it allows testing mixers at their real operating mode, levels of signals from LO oscillator stay invariable during parallel and series measurements. This testing method allows finding phase shift of both mixers at the same time.

III. THE METHOD OF THREE MIXERS

Another method, patented in United States in 1996 [2], is based on characterizing a mixer under test using a network analyzer and two reference mixers. The diagram of this method is in fig. 3. Mixer under test 2 and first reference mixer 6 are connected in series by IF inputs between port 1

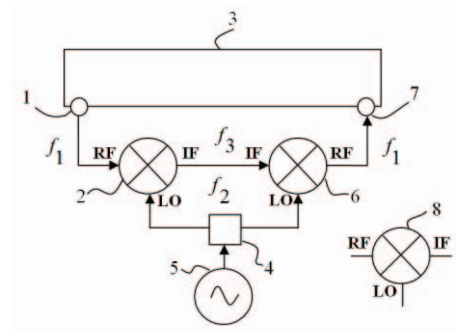

Fig. 3. Method of three mixers

and port 7 of vector network analyzer 3 (VNA). Test RF signal with frequency f_1 from the first port 1 of the VNA comes to the RF input of the mixer under test 2. LO inputs of mixers 2 and 6 are powered by signal with frequency f_2 from generator 5 through tee 4. As a result of frequency conversion mixer 2 generates signal with frequency $f_3 = f_1 - f_2$ on its IF port, that comes to the IF port of mixer 6, where it mixes with signal from generator 5. In the first reference mixer 6 signal with frequency $f_1 = f_3 + f_2$ is generated and comes to the second port 7 of VNA 3. With such configuration of mixers 2 and 6 VNA measures the sum of the phase shift between them as $\Sigma\varphi_{26} = \varphi_2 + \varphi_6$. Then mixer 6 is disconnected and replaced with second reference mixer 8. With this configuration VNA measures sum of phase shift between mixers 2 and 8 as $\Sigma\varphi_{28} = \varphi_2 + \varphi_8$. Finally, mixer under test 2 is replaced by first reference mixer 6 and VNA measures sum of phase shift between first and second reference mixers 6 and 8 as $\Sigma\varphi_{68} = \varphi_6 + \varphi_8$. By solving system (6):

$$\begin{cases} \Sigma\varphi_{26} = \varphi_2 + \varphi_6 \\ \Sigma\varphi_{28} = \varphi_2 + \varphi_8 \\ \Sigma\varphi_{68} = \varphi_6 + \varphi_8 \end{cases} \tag{6}$$

we can find absolute phase shift of mixer under test 2 as:

$$\varphi_2 = \frac{\Sigma\varphi_{26} + \Sigma\varphi_{28} - \Sigma\varphi_{68}}{2} \tag{7}$$

Advantages of this method are that the measurement process is relatively simple compared with the previous method, and only standard instruments such as a network analyzer are needed.

IV. Analysis

One of disadvantages of sum and difference method and method of three mixers are significant errors that are result of “parasitic connections” between mixer under test and reference mixer. But the main disadvantage of these methods is high amount of connections in the RF band. We developed flow graphs that describe connections between elements in fig. 1 in S-parameters system shown in fig. 4 and fig. 5.

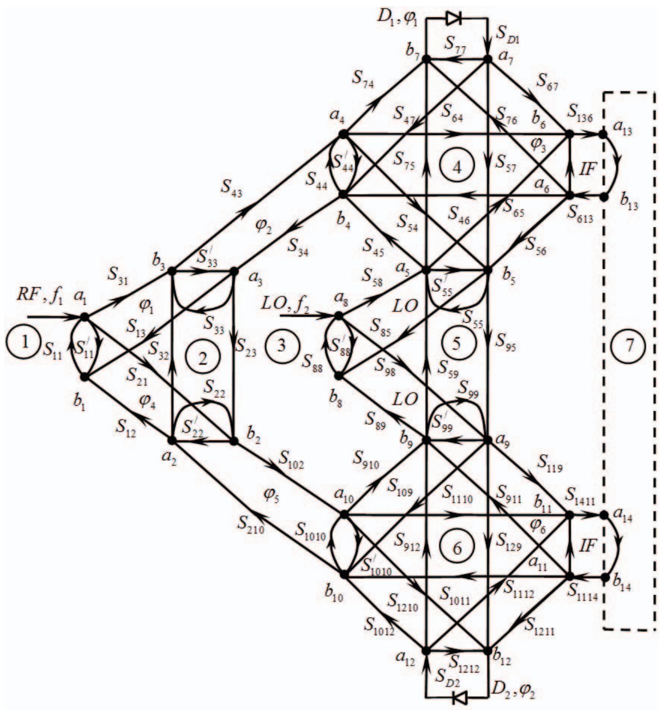

Fig. 4. Flow graph of mixers in parallel

Flow graphs in fig. 4 and fig. 5 that describe RF connections to measure sum and difference of phase shift between mixer under test 4 and reference mixer 6 allow making an error analysis of this method. From the graphs it can be seen that main errors are generated by the parasitic connections between mixer under test 4 and reference mixer 6 through the channels of LO generator 3. These parasitic ways are $S_{912} \cdot S_{59} \cdot S_{75}$ and $S_{57} \cdot S_{95} \cdot S_{129}$ because IF signals pass through them. To reduce these errors it is necessary to have a good isolation that is defined by ways S_{59} and S_{95}. The transition from RF generator 1 that generates test signal with frequency f_1 to the port $a_{13} - b_{13}$ of the vector voltmeter 7 can be characterized by (9):

$$S_{113} = \frac{S_{31}e^{j\varphi_{31}} S_{34}e^{j\varphi_{34}} S_{47}e^{j\varphi_{47}} S_{D1}e^{j\varphi_{D1}} S_{76}e^{j\varphi_{76}} S_{613}e^{j\varphi_{613}}}{1+N_1} \qquad (9)$$

where:

$$N_1 = S_{11}S'_{11}e^{j(\varphi_{11}+\varphi'_{11})} + S_{33}S'_{33}e^{j(\varphi_{33}+\varphi'_{33})} + S_{44}S'_{44}e^{j(\varphi_{44}+\varphi'_{44})} + S_{77}S_{D1}e^{j(\varphi_{77}+\varphi_{D1})} + S_{66}S_{13}e^{j(\varphi_{66}+\varphi_{13})}.$$

Analogically transition to the port $a_{14} - b_{14}$ of the vector voltmeter 7 can be characterized by (10):

$$S_{114} = \frac{S_{21}e^{j\varphi_{21}} S_{102}e^{j\varphi_{102}} S_{1210}e^{j\varphi_{1210}} S_{D2}e^{j\varphi_{D2}} S_{1112}e^{j\varphi_{1112}} S_{1411}e^{j\varphi_{1411}}}{1+N_2} \qquad (10)$$

where:

$$N_2 = S_{11}S'_{11}e^{j(\varphi_{11}+\varphi'_{11})} + S_{22}S'_{22}e^{j(\varphi_{22}+\varphi'_{22})} + S_{10}S'_{10}e^{j(\varphi_{10}+\varphi'_{10})} + S_{12}S_{D2}e^{j(\varphi_{12}+\varphi_{D2})} + S_{11}S_{14}e^{j(\varphi_{11}+\varphi_{14})}.$$

In denominators of these equations (9) and (11) there are only first order closed contours used and other are not taken in consideration because of their extremely low values. Ways from the RF generator 5 to the mixer diodes are constant during sum and difference measurements and do not influence accuracy. Sections of the flow graph in fig. 4 in ports $a_4 - b_4$, $a_{10} - b_{10}$, $a_6 - b_6$, $a_{11} - b_{11}$ are the places of RF connections that are used to organize phase shift sum and difference measurements. It is known, that during such connections in the RF mode instability of the coaxial connectors like male-female is about – 40 dB, that is equal to reflection coefficient $\Gamma = 0.01$. Electromechanical switches that are used for such measurements have VSWR in limits of 1.3-1.5. Error of phase shift measurement that as a result of bad coupling can be found as $arctg\left(\frac{VSWR-1}{VSWR+1}\right) = arctg(\Gamma_c)$, where Γ_c is reflection from the connection. From this we consider that one switch with VSWR=1.2 gives an error of 30’ (minutes). And with real value VSWR=1.3 error is 6°, with VSWR=1.5 error is 12°.

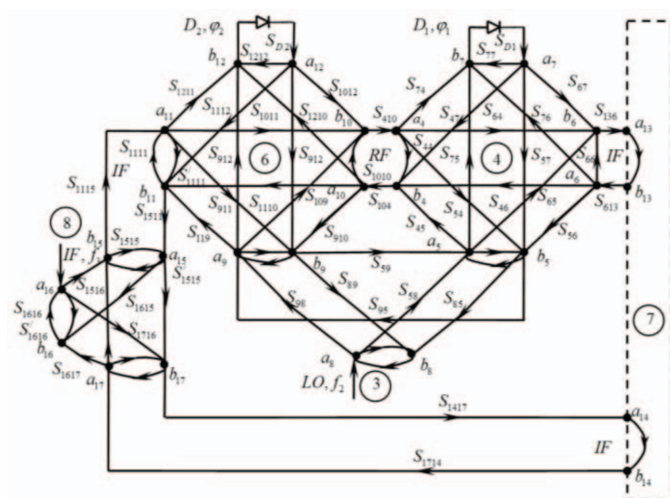

Fig. 5. Flow graph of mixers in series

The sum measurement mode is characterized by flow graph in fig. 5, which allows analyzing all ways of the test signal and electrical irregularities that test signal meets on these ways and this allows calculating their values. In this mode the basic device that forms test signal is IF generator (device 8 in fig. 1). Test signal from it goes through the tee to IF output of the reference mixer and to one of the inputs of vector voltmeter.

Transition from the IF generator to port $a_{13} - b_{13}$, of vector voltmeter can be characterized by (11):

$$S_{1613} = \left[\frac{S_{1516} e^{j\varphi_{1516}} S_{1115} e^{j\varphi_{1115}} S_{1211} e^{j\varphi_{47}} S_{D2} e^{j\varphi_{D2}} \cdot \ldots}{1 + N_3} \right] \times \\ \times \left[\frac{\ldots \cdot S_{1012} e^{j\varphi_{1012}} S_{410} e^{j\varphi_{410}} S_{74} e^{j\varphi_{74}} S_{D1} e^{j\varphi_{D1}} S_{67} e^{j\varphi_{67}} S_{136} e^{j\varphi_{136}}}{\ldots} \right]. \qquad (11)$$

where:

$$N_3 = S_{1616} S'_{1616} e^{j(\varphi_{1616} + \varphi'_{1616})} + S_{1515} S'_{1515} e^{j(\varphi_{1515} + \varphi'_{1515})} + \\ + S_{1111} S'_{1111} e^{j(\varphi_{1111} + \varphi'_{1111})} + S_{1212} S_{D2} e^{j(\varphi_{1212} + \varphi_{D2})} + \\ + S_{1010} S_{44} e^{j(\varphi_{1010} + \varphi_{44})} + S_{77} S_{D1} e^{j(\varphi_{77} + \varphi_{D1})} + S_{66} S_{1313} e^{j(\varphi_{66} + \varphi_{1313})}.$$

Transition to the second port of vector voltmeter $a_{14} - b_{14}$ can be characterized by (12):

$$S_{1416} = \frac{S_{1716} e^{j\varphi_{1716}} S_{14} e^{j\varphi_{1417}}}{1 + S_{16} S'_{16} e^{j(\varphi_{16} + \varphi'_{16})} S_{17} S'_{17} e^{j(\varphi_{17} + \varphi'_{17})}} \qquad (12)$$

A 4-pole network from flow graph $b_{10} - a_4$ and $a_{10} - b_4$ is most interesting for our analysis. While measuring sum of phase shift of two mixers, signal that is generated in reference mixer as a result of mixing signal of intermediate frequency f_3 with RF signal f_1 has low amplitude and needs amplification. Additionally, there is a wide spectrum of parasitic signals at the RF port of reference mixer that needs filtering. So, a band filter and amplifier need to be inserted between RF ports of reference mixer 6 and mixer 4 under test. Also, a variable attenuator should to be added between these RF ports when making a difference measurement. We define the sum phase shift of band filter, amplifier and attenuator as φ_3. Then when measuring difference phase shift we have $\Delta\varphi = \varphi_1 - \varphi_2 - \varphi_3$ and when measuring sum phase shift: $\Delta\varphi = \varphi_1 + \varphi_2 + \varphi_3$ and in the solution of (4) φ_3 is compensated and has no influence on the result.

Method of three mixers can be characterized by the flow graph equivalent to one in fig. 5, and the only difference is that mixers are connected with their IF ports instead RF ports.

In method of sum and difference and especially method of three mixers there is an measurement error defined by different reflection coefficients in the RF band of port of network analyzer/vector voltmeter, that has typical value $\Gamma_1 = 0.08$ (VSWR=1.2), and RF port of mixer under test. The value of RF port of mixer under test can be defined [5] by formula for 4-pole networks: $\Gamma_{inRF} = S_{12} S_{21} \Gamma_l / (1 - S_{22} \Gamma_l)$ where $\Gamma_l = S_{D1}$. In case $S_{D1} = 0.2$ (VSWR=1.5), $S_{11} = S_{22} = 0.08$ and $S_{11} \cdot S_{22} = 0.81$ using (13) we can calculate $\Gamma_{inRF} = 0.36$ (VSWR=2). In fig. 7 reflection coefficients Γ_1 and Γ_{inRF} are introduced as phasors.

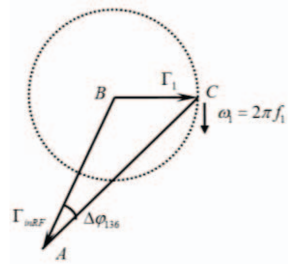

Fig. 6. Explanation for the formula (13)

Using cosine theorem for triangle ABC it is possible to calculate order of error value of mixer under test phase shift as a result of reflections with (13):

$$\Delta\varphi_{136} = \frac{\Gamma_1 \sin\left(\frac{2\pi l}{\lambda}\right)}{\sqrt{\Gamma_1^2 + \Gamma_{inRF}^2 - 2\Gamma_1 \Gamma_{inRF} \cos(\frac{2\pi l}{\lambda})}} \qquad (13)$$

where: l – is electrical length of the way from the port of network analyzer to mixer diode D1;

λ – wavelength of test RF signal with frequency f_1

In case $\sin\left(\frac{2\pi l}{\lambda}\right) = 1$ we can calculate that $\Delta\varphi_{136} = 12.4^\circ$, for $\sin\left(\frac{2\pi l}{\lambda}\right) = 0.5$ we will have 4.4˚. So it can be seen from this that misbalances between RF input of mixer and port of network analyzer causes high error of such mixer phase shifting measurement.

V. Conclusions

1. The errors of mixer measurements have rather high values and can cause significant influence on results of mixer characterizing process.
2. The method of sum and difference has lower error comparing to method of three mixers because of lower amount of connections and stable value of error which is a result of different reflection coefficients of mixer's RF port and port of network analyzer. This error is constant and it can be eliminated.
3. The method of sum and difference is much more complex to design and use comparing to method of three mixers.

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