DESIGN AND CALIBRATION OF IQ-MIXERS

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Abstract

An IQ-mixer consists of two balanced mixers and two hybrids. It provides two IF signals with equal amplitudes which are in phase quadrature. These devices play an increasing role in the processing of high-frequency signals, especially as modulators and demodulators. In addition, they allow to measure the amplitude and the phase of a high-frequency signal with respect to a reference signal or to control the phase during an amplitude measurement. Two different mixers were developed for RF-processing electronics at the TESLA TEST Facility Linac, having a center frequency of 1.5 GHz. The paper describes the basic concept of an IQ-mixer, the design of new devices and a calibration procedure. The errors introduced by the RF components and some methods to correct for them are discussed in detail. A method to realize the correction in software is presented, by which the resulting distortion is minimized. Finally, lab tests and some results are summarized.

1 INTRODUCTION

Resonant cavities were built to detect the transverse beam position in the TESLA Test Facility Linac (TTFL) [2]. The amplitude of the TM_{110}-mode excited by the beam yields a signal proportional to the beam displacement and the bunch charge, its phase relative to an external reference gives the sign of the displacement. The TM_{110}-signal at 1.5167 GHz decays with a time constant of about 200 ns, which can be treated as an amplitude modulation of the resonance. A homodyne receiving technique has been adopted to demodulate the signal by mixing it down to DC [3]. Phase drifts between the rf-signal and the reference signal - caused e.g. by temperature changes in long cables - have to be minimized or corrected.

IQ-Mixers

A so-called *IQ-Mixer* (or *Quadrature IF Mixer*) consists of two balanced mixers and two hybrids, as shown in Fig. 1. The RF-signal is introduced to the mixers in phase and the signal of the local oscillator (LO) through a quadrature hybrid; the outputs at the intermediate frequency (IF) are in phase quadrature. Assuming two input signals

$$E_R(t) = a(t)\cos(\omega_R t + \alpha) \qquad E_L(t) = b\cos(\omega_L t)$$

where the LO-amplitude b is above its drive-level[1], we get for an ideal IQ-mixer at both IF-outputs

Mixer 1 $\quad V_i(t) = a(t)\cdot K\cdot\cos(\omega_L t)\cos(\omega_R t + \alpha)$ (1)

Mixer 2 $\quad V_q(t) = a(t)\cdot K\cdot\sin(\omega_L t)\cos(\omega_R t + \alpha)$ (2)
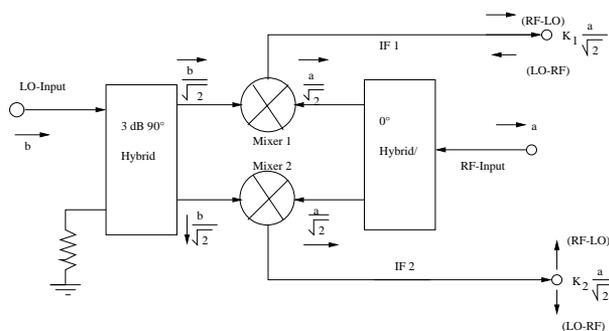
Figure 1: Block diagram of an IQ-mixer

This results in a coordinate system, where the vector of the output signals $V_i(t)$ and $V_q(t)$ rotates with the IF-frequency (Fig. 2). If the frequencies of both input signals are identical, this vector is fixed. For $\alpha = 0$, the amplitude R of this vector and its instantaneous phase ϕ are given by

$$R = \sqrt{V_i^2(t) + V_q^2(t)} = K\cdot a(t) \qquad (3)$$

$$\phi = \arctan(V_q(t)/V_i(t)) \qquad (4)$$

Figure 2: Polar plot of the I- and the Q-signal

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[1]The output signal depends only on the rf-signal level, a mixer-constant K which includes also the conversion loss, and the phase between both signals.

These devices play an increasing role in the processing of high-frequency signals, especially as modulators and demodulators. In addition, they allow to measure the amplitude and the phase of a high-frequency signal with respect to a reference signal or to control the phase during an amplitude measure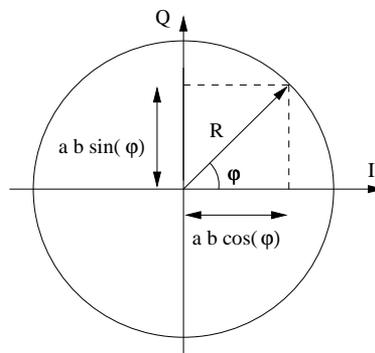ment. Here, IQ-mixers were developed to measure the resulting TM_{110}-envelope and to detect the sign of the beam position. The advantage is, that no additional phase stabilization or phase adjustments are needed.

2 DESIGN AND REALIZATION

Design of Narrowband IQ-Mixers

For LO-signals above the specified LO drive-level, small LO amplitude unbalances between both mixers do not effect the mixer output signal. In principle, the 90°-hybrid and the power divider can be exchanged. Very often the power divider is placed at the rf-input, since it can be realized with a much higher amplitude balance. Usually, a matched pair of mixers is needed, having identical losses and mixer constants. Here, standard mixers were used and the errors were corrected in a *calibration*.

Figure 3: IQ-mixer, board-layout for the MD-614

Two different mixer-types were used for the TTFL-electronics: the M2G (by Watkins-Johnson) and the MD-614 (by M/A-COM). Their drive-level is $+7$ dBm for a single mixer and the rf-compression point is 0 dBm. Other important parameters are given in table 1. Because of the different packaging styles, two slightly different boards using the TMM10 of ROGERS were developed. One built for the MD-614 is shown in Fig.3. The power divider is realized by a Wilkinson-divider, the 90°-hybrid as a branchline coupler (to the left in Fig.3). In Fig.4, this board is rotated and the IF-amplifiers integrated on the board are shown in the upper and lower left corner.

Errors of an IQ-Mixer

Equation (3) and eqn.(4) are true for ideal circuits. All errors of real structures can be divided into three categories:
DC-offsets: They are mainly caused by the mixers and by DC-signals introduced through the additional IF-amplifiers. A DC-offset causes the circle to be shifted from the origin of the IQ-coordinate system.

parameter	M2G	MD-614
RF-frequency [GHz]	$1.0 - 2.2$	$0.7 - 2.0$
LO-frequency [GHz]	$0.3 - 3.5$	$0.7 - 2.0$
IF-frequency [GHz]	$DC - 1.2$	$DC - 2.0$
min. Isolation LO/RF	25 dB	20 dB
DC offset (typ.)	2 mV	3 mV
Conversion Loss (max.)	9.5 dB	8.0 dB

Table 1: Different mixers used in the design

Figure 4: Complete IQ-mixer using the MD-614.

Amplitude errors: The amplifications or the attenuations of both channels are slightly different, due to unbalances in both hybrids, different conversion losses in the mixers and different gains in both IF-amplifiers. The resulting curve in the IQ-system is an ellipse (see also Fig. 5).
Phase errors: These errors are caused by phase unbalances in the 90°-hybrid and by different electrical length.

Figure 5: Errors and their influence on the IQ-system

The effect of these errors on an amplitude or a phase measurement can be estimated. To develope a calibration scheme, eqn. 1 and eqn. 2 have to be corrected

$$V_i^* = K \cdot \left(\frac{a(t)}{2} \pm k_1 \right) \cdot k_2 \cdot \cos \left(\omega t \pm \varphi_1 \right) \quad (5)$$

$$V_q^* = K \cdot \left(\frac{a(t)}{2} \pm k_3 \right) \cdot k_4 \cdot \sin \left(\omega t \pm \varphi_2 \right) \quad (6)$$

where k_1,k_3 are DC-constants, k_2,k_4 are amplitude factors, and φ_1,φ_2 take into account the phase correction.

3   CALIBRATION

There are two ways to correct for the errors mentioned above: in the hardware by adjusting all gains and phases in a test setup, and in the software. In the latter a calibration signal is used to measure the response of the mixer under test. The calibration constants of eqn.(5) and (5) are determined by correcting these measurements - usually ellipses as sketched in Fig.5 - to ideal circles. This is done by an optimization program.

Measurements

In the test setup at the TU Berlin the signal generated by a RF source is splitted into two signals by a power divider. One signal is amplified and connected to the LO-input of the mixer under test, the other one is connected to the RF input. The phase shifter in the rf-arm is used to change the phase by $0^0 \cdots 300^0$ at a fixed amplitude. Both outputs of the IQ mixer are amplified and displayed on an Oscilloscope, controlled by a PC running a VEE application. For ideal mixers, the resulting IQ-curve should be a circle and the transformation into a R-φ-diagram a flat line.
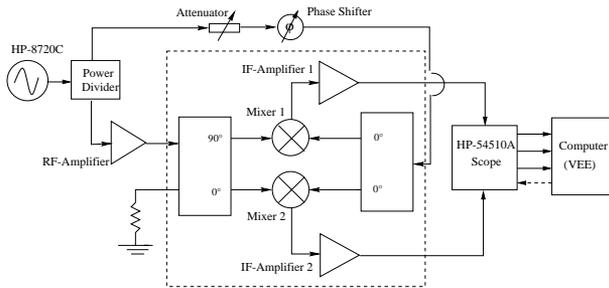
Figure 6: Test of I/Q-mixers using a phase shifter

Error Correction and Optimization

There are several optimization strategies. The one used here is based on the behaviour in the R,ϕ-plane: the variation of the function $R(\phi)$ is minimized to get this 'flat line'. This is done in a MATLAB-program by using the Non-linear Least Square Method. The program searches for an optimum set of k-parameters as long as a lower limited for the difference between the largest and the smallest R-value is not reached. It is based on the error function:

$$F = \sum_{F_i}^{F_n} (G_{ist} - G_{soll})^2 \Rightarrow 0 \qquad (7)$$

(G is a weighting). The constants are determined for more than 5 calibration measurements at different amplitudes. Their average is than used to correct each measurement.

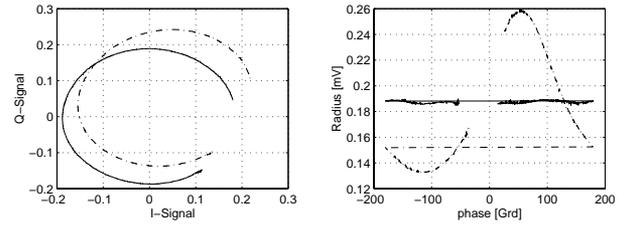Fig.7 shows the measured and the corrected voltages for one of the calibrated M2G-mixers.

Figure 7: Test results: Left the IQ-system, to the right R versus ϕ. The dashed lines show the uncorrected measurements, the solid lines display the results after correction.

4   CONCLUSIONS

Narrowband IQ-mixers using two different types of commerical mixers have been built for an application at 1.5167 GHz. An error correction scheme based on calibration measurements has been developed to avoid any (complicated) hardware correction. It turned out, that nearly all errors can be corrected. The remaining error of an amplitude measurement is less than 5%. All mixers containing the M2G were installed in the TTFL-electronics because of their higher isolation and lower costs. Some calibration results for these devices are summarized in table 2.

parameter	S/N 01	S/N 02	S/N 03
dc-offset in I [mV]	−39.80	−61.40	−54.20
dc-offset in Q [mV]	65.10	−24.70	−32.80
amplification of IQ	0.94	0.979	0.95
phase error [mrad]	−0.201	−0.11	−0.14

Table 2: Calibration results of 3 electronic channels

The next steps are to reduce the errors introduced by impedance unbalances of the phase shifter and to apply this method to the calibration of IQ-mixers developed at 12 GHz. The impedance unbalances causes a slight amplitude variation at the output of the calibration module [3].

Finally, we would like to thank Reinhard Schroeder for building all these devices.

5   REFERENCES

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[2] R. Lorenz et al., *First Operating Experiences of Beam Position Monitors in the TESLA Test Facility Linac*, in Proc. of the PAC 97, Vancouver, May 1997

[3] R. Lorenz et al., *Electronics for the TTFL Cavity-Type Beam Position Monitor*, these proceedings