Improvement of RF Vector Modulator Performance by Feed-forward Based Calibration

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Abstract. *RF Vector Modulator enables independent control of a narrowband RF signal amplitude and phase. Unfortunately practical realization of an analog vector modulator suffers from misbalances and imperfections in the I and Q signal paths. Use of a feed-forward based calibration can compensate for them and significantly improve RF performance and control accuracy of a real vector modulator. Achieved improvements and results on a small series of vector modulator based phase shifters using feed-forward calibration are presented.*

Keywords

Phase shifter, vector modulator, calibration, feed-forward, phase error, set point.

1. Introduction

Main motivation for development of the Vector modulator based phase shifter was to prepare a general-purpose module for phase and amplitude correction of narrow band harmonic signals in the CERN's SPS (Super Proton Synchrotron) accelerator Low-Level RF system. The digital control interface allows to control the phase/gain values remotely as a function of accelerating frequency, machine cycle, timing, analog set-point or manual control. A long term stability and absolute phase control accuracy is required.

Vector modulation is a well known and effective technique of amplitude and phase control for harmonic signals. Unfortunately, if realized in an analog domain using real components, it is difficult to achieve high control accuracy as real devices suffer of e.g. phase and amplitude misbalances in the I/Q demodulator (I and Q signal path symmetry), analog multiplier imperfections or isolation problems in the input and output splitting/combining networks. All these imperfections contribute to the amplitude and phase errors in the vector modulation process. On top of that, these imperfections could also be frequency and amplitude dependent on the signal and respective phase shift and amplitude set points. Thanks to a feed-forward calibration and correction technique, we are able to minimize these negative factors significantly and improve the vector modulator performance and regulation accuracy by a pre-distortion of the I and Q modulation signals.

The designed vector modulator based phase shifter is currently used as a time of flight compensation for the RF cavity return signals during the lead ion acceleration cycle in the SPS. The system was originally designed to accelerate much lighter protons. In order to accelerate "slower" moving heavy ions, the RF phase of the cavities must follow their still increasing velocity through the acceleration cycle giving a total phase error in order of 150° (@ 200 MHz). When the ions become sufficiently relativistic the system continues acceleration with all cavities phased as in a regular proton cycle [1]. All set points are dynamically changed through the acceleration cycle by the control system using digital serial links. A set of 6 modules was installed in the Faraday Cage of SPS and being used since August 2009.

The module was designed to be versatile so it will be soon used also as RF phase reference compensation in the fiber optic links (beam travels in the machine at a speed close to the speed of light while the light in connecting optical fibers is slower resulting in a phase-shift at the reception point), or an IF general purpose vector modulator. As the device is controlled by a programmable logic device (FPGA) and equipped by all standard communication ports used in the SPS low-level RF system (serial link, timing, analog input) its function could be easily adapted to almost any potential application.

2. Vector Modulator

The input signal is transformed to in-phase and quadrature components by a 90° hybrid. These components are then multiplied by vector representation of the desired vector modulation coefficients and summed to get the output signal according to the equation

$$r(t) = G \cdot \cos(\omega_0 t - \Delta\varphi) \tag{1}$$

where $\cos(\omega_0 t)$ is the input signal, G is the desired gain and $\Delta\varphi$ the desired phase-shift. The relation between G and $\Delta\varphi$

and the modulation components *I* and *Q* ([2], [3]) is then defined by equations (2) and (3).

$$G = \sqrt{I^2 + Q^2}\ , \tag{2}$$

$$\Delta\varphi = \arctan\left(\frac{Q}{I}\right). \tag{3}$$

Furthermore the modulation components could be then transformed from the polar G-Δφ notation to the I-Q notation used for the actual modulation as follows:

$$I = G \cdot \cos(\Delta\varphi)\,, \tag{4}$$

$$Q = G \cdot \sin(\Delta\varphi)\,. \tag{5}$$

Real parameters of all involved components (quadrature hybrid, multiplier, I and Q DACs, combiner) define quality and accuracy of the modulation.

Gain error, I-Q phase imbalance or a DC offset of the I and Q DACs will introduce amplitude and phase errors to the output signal according the equations (2) and (3). Nonlinearities of the multiplier could further introduce more phase and amplitude errors dependent on the set point value.

Modern systems minimize the I and Q signal path imbalance by integration of the vector modulator onto one chip, where a high level of symmetry and balance could be guaranteed by design. Topic related examples of other techniques are presented in [4] and [5].

3. Feed-forward

Feed-forward techniques are based on an inverse distortion of the generated signal to the distortion of the following processing chain [6]. The distortion techniques are based on the detailed knowledge of the system transfer function, which is then implemented to the feed-forward correction algorithm.

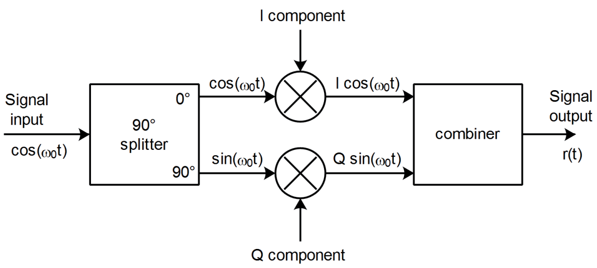

Fig. 1. Diagram of a general vector modulator.

The general feed-forward pre-distorted signal is described by the equation

$$s_{FF}(t) = s(t) \cdot \frac{1}{h} \tag{6}$$

where the $s(t)$ is the desired system output, *h* is transfer characteristic of the following signal processing chain and the $s_{FF}(t)$ represents the signal which needs to be generated to achieve the correct output signal $s(t)$. For a static system, the transfer function *h* is time invariant.

4. Experimental Realization

The experimental realization of the feed-forward correction for the vector modulator based phase shifter is shown in Fig. 2. The feed-forward correction is implemented in a programmable logic device. The phase shifter aimed to be used as a time of flight compensation where a total calculated phase shift could reach values up to million degrees. After summing up of all phase correction contributions the unwrapped phase value is wrapped into a -180 to +180° range. As the I and Q modulation values are calculated by CORDIC algorithm an additional gain control capability in a limited range comes "for free".

RF parameters listed in Tab. 1 were set as goals for the experimental realization.

Parameter	Value
Center frequency	200.222 MHz and 10.7 MHz
Nominal Gain	0 dB
Gain control range	-6 to +3 dB
Gain control resolution	0.1 dB
Phase shift control range	-180 to +180°
Phase shift resolution	1/32° (0.03°)
Absolute phase shift accuracy (setpoint vs. measurement)	<0.5°

Tab. 1. Design parameters and goals, both RF and IF versions.

The operating point of the analog multipliers was set such that nonlinearities and compression could be neglected in the range of signal levels where the modulator operates. The feed-forward correction therefore calculates the predistortion of the I and Q values only as a function of the primary control quantity what is in this case the desired phase set point $\Delta\varphi$.

The measurements shown in section 5 display the uncorrected modulator phase-shifter performance (gain and phase difference versus the set point) as a function of the requested phase set point value.

To correct the deviations (focused on compensation of *I* and *Q* imbalance and amplitude error) a generic mathematical error model was built and later implemented into the FPGA according to the equations

$$I_{OUT} = a \cdot \left(I_{IN} + b \cdot Q_{IN}\right), \tag{7}$$

$$Q_{OUT} = c \cdot \left(Q_{IN} + d \cdot I_{IN}\right) \tag{8}$$

where *a*, *b*, *c* and *d* are correction parameters (*a*, *c* for amplitude and *b*, *d* for *I*, *Q* imbalance) of input signals I_{IN} and Q_{IN} to the output signals I_{OUT} and Q_{OUT}.

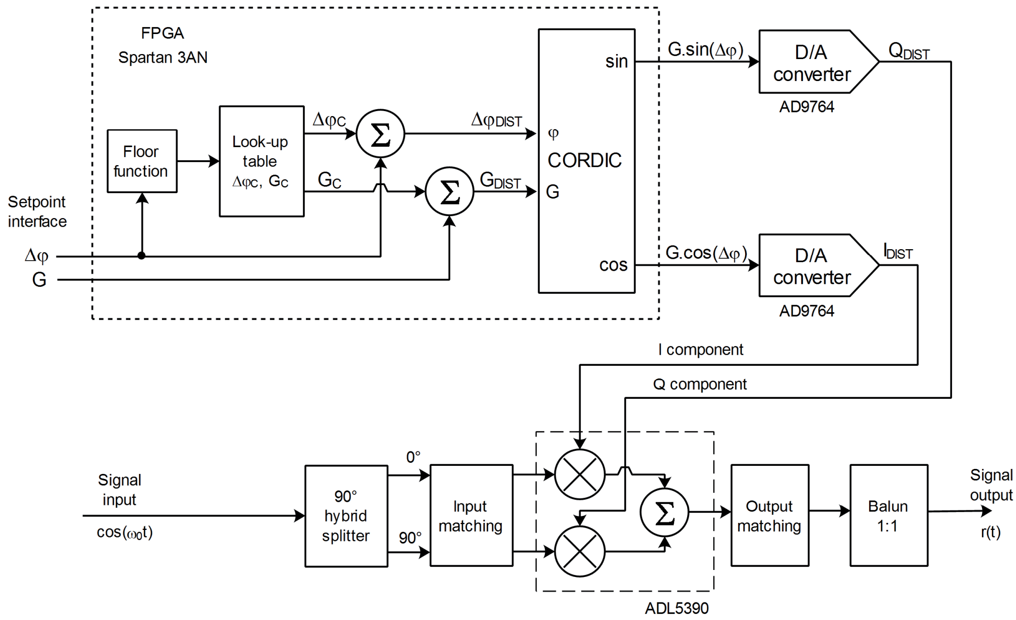

Fig. 2. Diagram of the realized vector modulator phase shifter.

The correction parameters of the model were found experimentally. The phase and amplitude control error was improved by factor of 2 to 3, what was still not sufficient. Implementation of a more complex compensation model with additional terms would use too many FPGA resources and would make the calibration process overwhelmingly complicated. Therefore in order to obtain the required performance the error model compensation was disregarded and a fixed look-up table (LUT) storing correction parameters G_C and $\Delta\varphi_C$ was implemented instead.

Analysis of the measured data showed that required design parameters will be reached if the correction is applied with a not more than 1° granularity (i.e. one correction value for each degree of the set point) yielding to a LUT with a decent size of 361 items, covering range from -180° to +180°. Address of the LUT is therefore derived from the integer part of the phase shift set point $\Delta\varphi$ value. The look up table stores a phase correction values $\Delta\varphi_C$ (8 bits, correction +/- 8°) and the gain correction values G_C (12 bits, correction +/- 2 dB). The correction is added (phase) to or multiplied (gain) with the required phase and amplitude set point values, later transformed by the CORDIC algorithm to the pre-distorted values I_{DIST} and Q_{DIST}. The procedure is described by the equations (9), (10), (11) and (12).

$$G_{DIST} = G + G_C(\Delta\varphi)\,, \tag{9}$$

$$\Delta\varphi_{DIST} = \Delta\varphi + \Delta\varphi_C(\Delta\varphi)\,, \tag{10}$$

$$I_{DIST} = G_{DIST} \cdot \cos(\Delta\varphi_{DIST})\,, \tag{11}$$

$$Q_{DIST} = G_{DIST} \cdot \sin(\Delta\varphi_{DIST})\,. \tag{12}$$

The Analog Devices chip ADL5390 – a complete dual vector multiplier with adder, is used as a vector modulator [7]. The analog I and Q components are generated by two fast 14 bit D/A converters AD9764. The logic is implemented in the Spartan 3AN FPGA device clocked at 50 MHz. The device contains the described feed-forward correction algorithm. The phase shifter center frequency 200.222 MHz or 10.7 MHz is defined by the quadrature hybrid and output transformer used (Tab.1). The hardware is capable to perform the modulation at a full 50MHz rate.

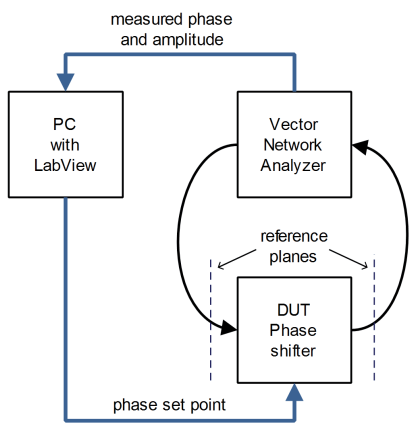

Fig. 3. Phase shifter calibration measurement test bench.

5. Results

The correction data for the implemented feed-forward correction method has to be evaluated from the measurements of the uncorrected module transfer function. The measurement was organized according to Fig. 3. The transfer function was measured by a vector network analyzer (VNA) which is calibrated to the reference planes located at the input and output connector of the phase shifter module. The measurement process was automated by LabView software. The measurement process starts with a setup of the actual set point value, followed by a short delay to get a clean sweep and consequent readout of the phase and amplitude values from the VNA. The set of these measurements in the range from -180° to +180° with step of 1° allows to calculate the correction values for the gain G (in dB) and the phase shift $\Delta\varphi$ by the equations:

$$G_C = G - G_M \,, \tag{13}$$

$$\Delta\varphi_C = \Delta\varphi - \Delta\varphi_M \tag{14}$$

where the variables with index M represent measured values and index C represent feed-forward correction values. The process of extraction and implementation of the correction data is realized in a single iteration. If better than <0.5° and <0.1 dB accuracy is required a second iteration and fine improvement of the calibration table could be done. There are also enough resources in the FPGA available to implement a LUT with finer granularity providing further improvement in the accuracy.

The measurement resolution and precision is given by the VNA device, for this application a resolution <0.05 dB and 0.1° is sufficient.

The measurements were realized on a small series of six SPS Phase shifters [8] (Fig. 7) which helped to confirm a validity of the results.

5.1 Phase Calibration

Fig. 4a shows the phase error as a function of the desired phase set point value. The maximum error of about 4° was reduced to be below 0.5° (Fig. 4b, equivalent of 6.9 ps delay for a 200 MHz signal). The mean value of the phase error was on the average decreased to 11.4% of the mean value of the phase error without the feed-forward correction and the standard deviation is similarly reduced to 13.8% (from 1.23° to 0.17°). The improvement of the phase error parameter is significant especially for the reduction of the maximal error value and the decrease of the standard deviation value.

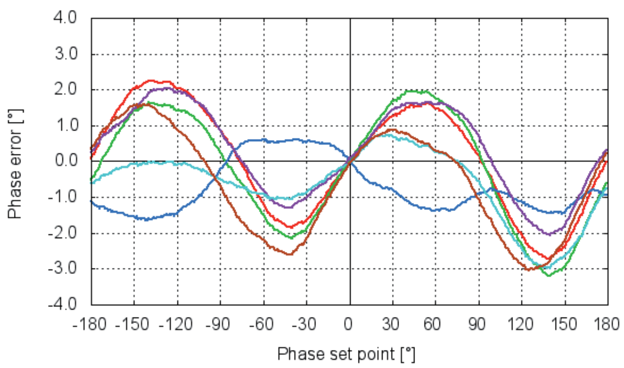

Fig. 4a. Phase shift error vs. phase set point without feed forward correction. 6 modules, frequency 200.222 MHz.

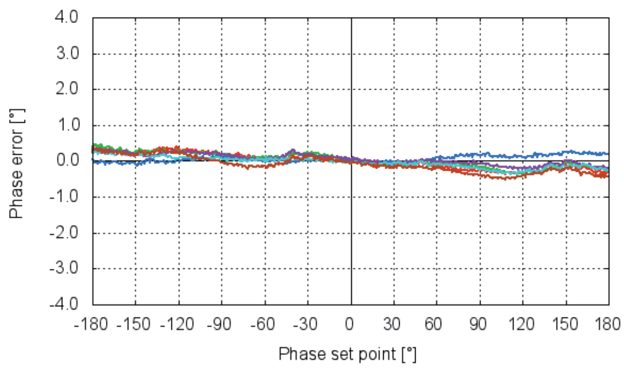

Fig. 4b. Phase shift error vs. phase set point with feed forward correction. 6 modules, frequency 200.222 MHz.

5.2 Gain Calibration

The goal of the gain calibration is to achieve a flat module gain over the entire range of phase set points. The mean value of gain is not important because the realized phase shifter offers fine gain adjustment to match the module gain to the one in "hard bypass" mode[1].

After implementation of the feed-forward correction (Fig. 5b), the mean value of the standard deviation of the

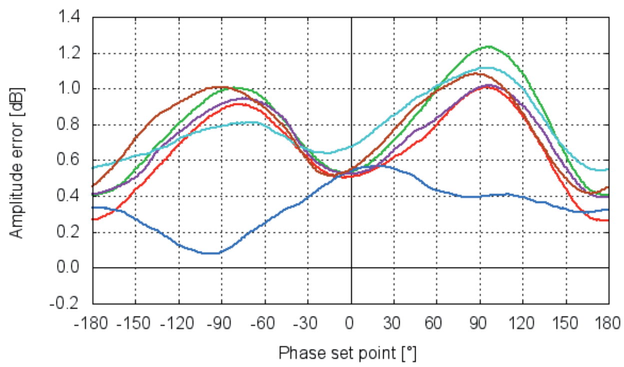

Fig. 5a. Module gain error vs. phase set point without feed forward correction. 6 modules, frequency 200.222 MHz.

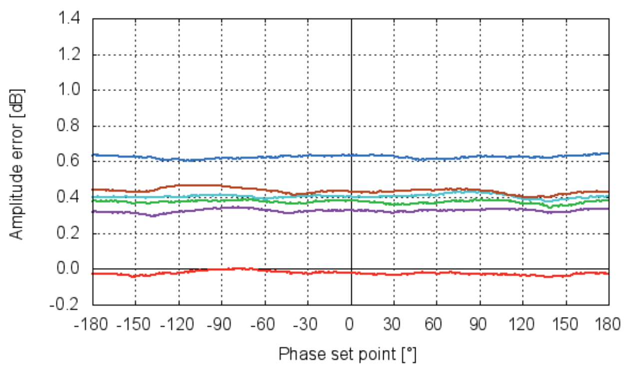

Fig. 5b. Module gain error vs. phase set point with feed forward correction. 6 modules, frequency 200.222 MHz.

[1] For troubleshooting and machine reliability/availability reasons the module could be hard bypassed by a RF relay and a piece of transmission line. The module was designed to have exactly the same gain, phase and group delay in default configuration (G = 0 dB, $\Delta\varphi$ = 0°) as in hard bypass, so it is transparent for the operation when it fails.

module gain was on the average reduced to 5.7% of the original value without correction (Fig. 5a). The mean value of the standard deviation for the output level is below 0.02 dB and maximum output level error in respect to its mean value of every module is below 0.04 dB.

5.3 Frequency Dependency

The vector modulator core is designed as very wideband. The modulator chip covers frequency range from few MHz to 3 GHz and the modulation bandwidth could reach tens of MHz.

The operational bandwidth is however limited by the analog quadrature hybrid used. The SPS phase shifter (RF version) works at an almost constant frequency of 200.222 MHz with a very narrow frequency excursion (+1/ -2 MHz). The RF parameters were verified also as a function of the RF signal frequency. One module of the series was measured at frequencies 199.300, 200.222 (nominal) and 200.400 MHz what is 1.1 MHz bandwidth.

In this range, the phase error has maximum scatter of 0.027° (Fig. 6a) and the gain error maximum 0.016 dB (Fig. 6b) with respect to the center frequency values in the whole phase set points range -180° to +180°. These values show frequency stability of the phase shifter parameters and effectiveness of the feed-forward correction in the required frequency range. The phase shifter can be used in the declared frequency range without relevant influence on the observed parameters.

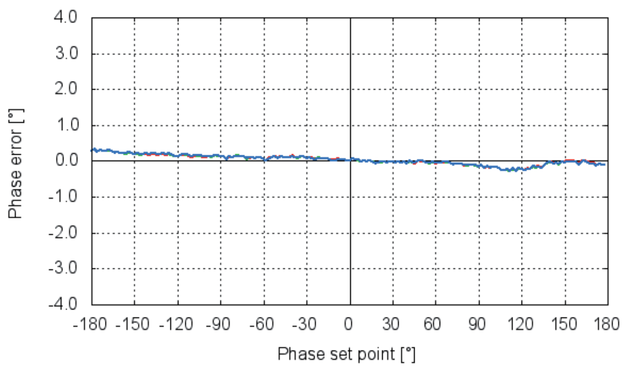

Fig. 6a. Phase shift set point vs. signal phase shift without digital calibration, 1 module, 199.300, 200.222 (nominal) and 200.400 MHz

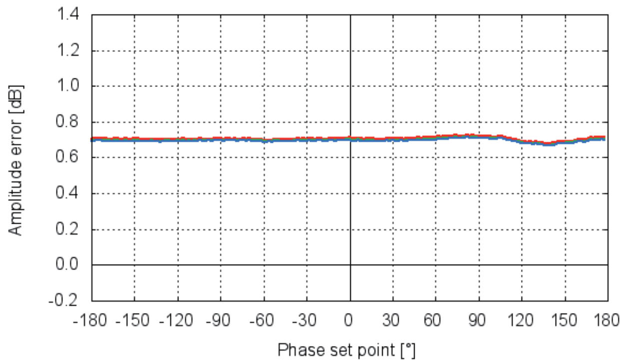

Fig. 6b. Phase shift set point vs. output signal amplitude level with digital calibration, 1 module, 199.300, 200.222 (nominal) and 200.400 MHz

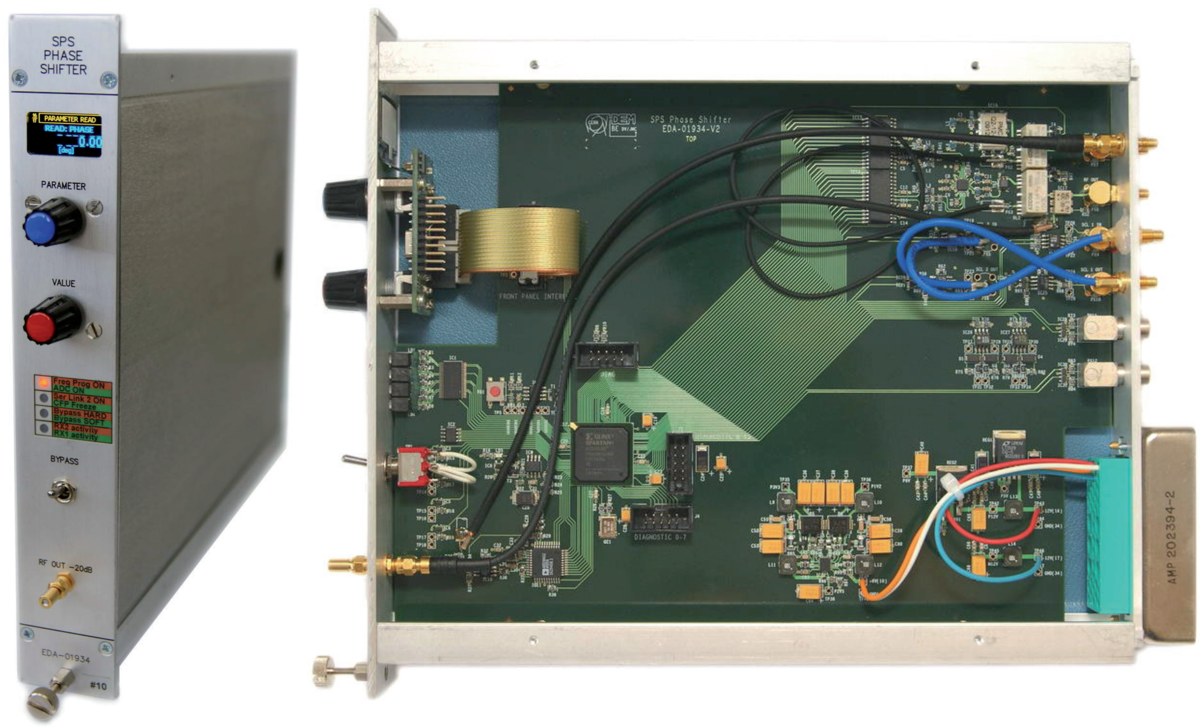

Fig. 7. Photo of the realized SPS Phase shifter – a NIM format module with serial control link and human interface.

6. Conclusions

The presented technique of feed-forward based calibration of the digitally controlled analog phase shifter with vector modulator is able to significantly reduce imperfections of the analog vector modulator part. This reduction improves phase and amplitude parameters of the modulator in the entire range of the phase set points.

For the experimental realization of small series of six phase shifters, the reduction of the mean value of the phase error down to 11.4% and reduction of the standard deviation down to 13.8% of the value without the feed-forward technique was achieved. The gain standard deviation was on the average reduced down to 5.7%. The RF parameters are also insensitive to frequency changes within the specified working bandwidth (1.1 MHz at 200.222 MHz). The maximal phase error difference within this bandwidth was 0.027°. The gain error has the maximum difference below 0.02 dB.

The presented feed-forward calibration effectively improved accuracy and precision of the phase shift and gain control approximately by one order of magnitude.

Next development will be focused on tracking of long term stability of the vector modulator device and its influence on all mentioned parameters.

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