Automated Measurement and Evaluation of 6-bit Amplitude and Phase Control Modules

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***Abstract*—Digital attenuators and phase shifters can be used to implement vector modulators, used in phased array antennas. Measuring all the possible gain-phase states requires an automated approach. This paper presents the automated test setup used to measure a 3-6 GHz 12-bit vector modulator, which uses a 6-bit attenuator and a 6-bit phase shifter to vary signal amplitude and phase. A Python program was written to automate the testing of all 4096 possible states, to better understand the potential performance of the vector modulator. The combined performance is presented and is considered outside the intended frequency ranges of the modules. This paper outlines the technical considerations for performing and processing the measurements and highlights the advantages of an automated test setup.**

I. Introduction

Digital step attenuators and phase shifters can be combined to control signal amplitude and phase, effectively forming a vector modulator (which can be used in phased array antennas for beamforming). It is desirable to measure these devices to determine their accuracy and whether different states are optimal for each desired phase and attenuation level. Measuring and processing all 4096 states for 12-bit control is too time intensive to perform manually, so automated approaches are used. This paper describes the automated test setup used to control and measure two 6-bit amplitude and gain control modules in series (EVAL-HMC624ALP4 and EVAL-HMC649A from Analog Devices). The measured results are presented and different measures to evaluate the performance are explored.

II. Measurement Test Bench

A. Setup

The purpose of the setup is to measure the S-parameters of the modules in each of the gain-phase states. The physical measurement setup is shown in Fig. 1. The S-parameters are measured by the vector network analyser (Keysight E8364B PNA). The .s2p files are copied to and stored on the laptop, which communicates with the PNA using the GPIB (General Purpose Interface Bus) interface. The gain-phase states of the modules are set by the voltages applied to the six control pins on each evaluation board. The digital voltages are set using a digital I/O device (National Instruments USB-6501), which is controlled by the laptop and nominally outputs 5 V or 0 V. The upper voltage level that is applied to the control pins can be changed using the switch boards (ADI EVAL-ADG5412FEBZ), which allow the 5 V to be changed to the output of a DC supply. The switch boards contain SPST switches, each switch controlled by an output from the I/O device.

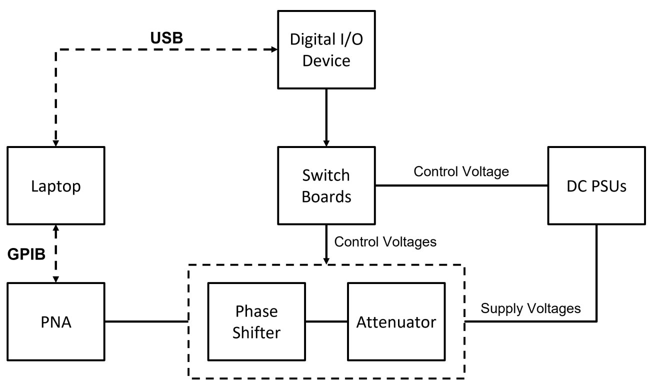


Fig. 1: Block diagram showing the measurement setup.

B. Software

The measurement setup is automated using Python; this is used for both the front end and the back end. The PyVISA package is used to communicate with the PNA; PyVISA uses VISA (Virtual Instrument Software Architecture) to control devices and SCPI (Standard Commands for Programmable Instruments) commands can be used. The NI-DAQmx package is used to communicate with the I/O device; this uses the NI-DAQmx driver rather than VISA. For ease of use, a simple graphical user interface is designed with the Tkinter library, for ease of use; a screenshot from the program is shown in Fig. 2.

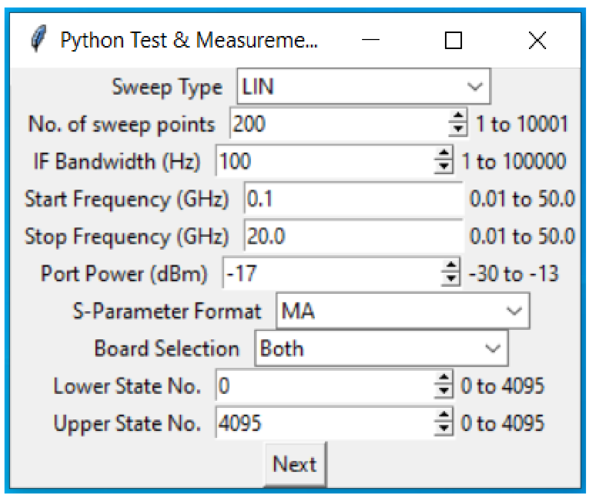


Fig. 2: Screenshot of parameter input screen

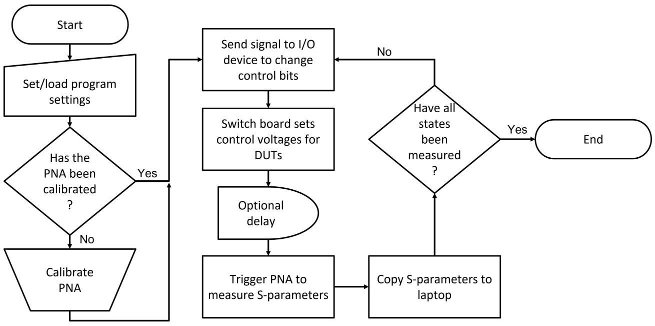


Fig. 3: Flow chart of the measurement process

C. Processes

Fig. 3 shows a flow chart of the main steps in the measurement process. Some of the steps are covered in more detail below.

1) Automated stages: An optional delay was added during development to make sure the S-parameter sweep did- not start before the control voltages and device states had settled. S-parameters were measured and compared using delays up to one second. No effect was observed so the delay was removed for the actual measurements.

Each s2p file is copied to the laptop after every measurement sweep for convenience, and so that they can be viewed remotely during the measurements. Removing this stage, and copying the files after all the measurement sweeps are completed, reduces the measurement time by approximately 12%.

2) Manual stages: The set/load program settings and calibration processes are manually carried out. In the former, parameters like the number of sweep points and the frequency range are set, which need to be set manually. These can be loaded from past runs to save time. The PNA is calibrated manually using an ECal module (Keysight N4693A).

D. Measurement Time

Measuring 4096 states takes 4 hours 48 minutes (200 frequency points per sweep). This can be reduced to 4 hours 13 minutes if the s2p files are copied after all the sweeps are complete. Measuring the amplitude and phase modules separately (64 states each) takes 6.5 minutes. The equivalent manual measurement time can be estimated as roughly 9 days if each measurement loop lasts 1 minute and the test engineer works 8-hour days. The automated measurements are considerably faster than the manual approach, and further reductions in the measurement time are possible, such as by running the Python script on the PNA directly, instead of on a laptop. Other benefits of the automated test bench include: the avoidance of human error, the results can be monitored remotely, and the setup can be left unsupervised

III. Definitions

A. State Position Error

Equation (1) is used to quantify the distance between the ideal gain-phase states and the actual performance,

$$SPE_{RMS} = \sqrt{\frac{\sum_{i=0}^{N-1} \left(\frac{|E_i|}{R_i} \right)^2}{N}} \tag{1}$$

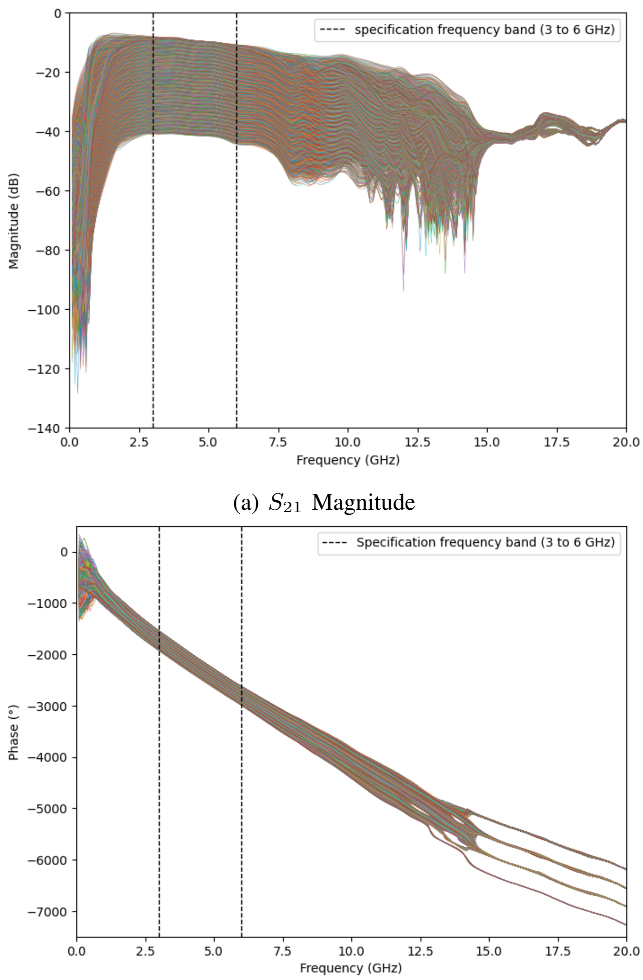
where i is the state number, E_i is the error vector between the measured (normalised) and ideal S_{21} points, R_i is the amplitude of each ideal point and N is the number of measured states (4096 using all 12 bits).

State position error (SPE) is similar to error vector magnitude (EVM), but multiple reference amplitudes are used instead of only one (R_i instead of R_0) to account for the increasing distance between the linear S_{21} magnitude of states as the attenuation level increases. The number of points in each amplitude level is the same (64 points per attenuation level), so larger error vectors can be tolerated in higher gain states before adjacent states become ambiguous.

B. State Numbers

The 'State Numbers' on the x-axes in Fig. 7, 8 and 10 refer to the decimal form of the DC control bits for the modules.

In binary form, each state number is 12 digits long: bits 6-11 control the amplitude module and bits 0-5 control the



(a) S_{21} Magnitude

(b) S_{21} Phase

Fig. 4: Measured results of the 12-bit phase and gain module cascade

phase module. When all the control bits are 0, the amplitude module is in its maximum attenuation state and the phase module is in its 0° reference state. Therefore, the phase cycles through 360° every 64 states and the attenuation level reduces from its maximum level in states 0-63 to its minimum level in states 4032 to 4095.

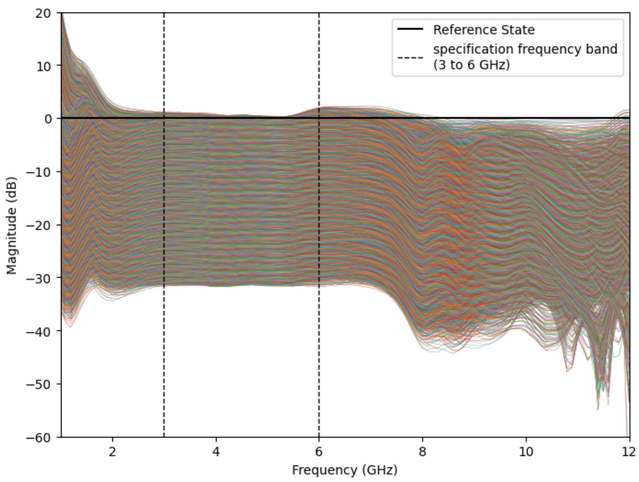
IV. Results and Discussion

The measured S_{21} magnitude and phase for all states are shown in Fig. 4. The modules perform well in the specified band of 3-6 GHz. The gain and phase are less uniform outside this band but the modules could potentially operate at a lower bit resolution. Both S_{21} curves converge near 14 GHz, so the modules cannot be used close to or above this frequency.

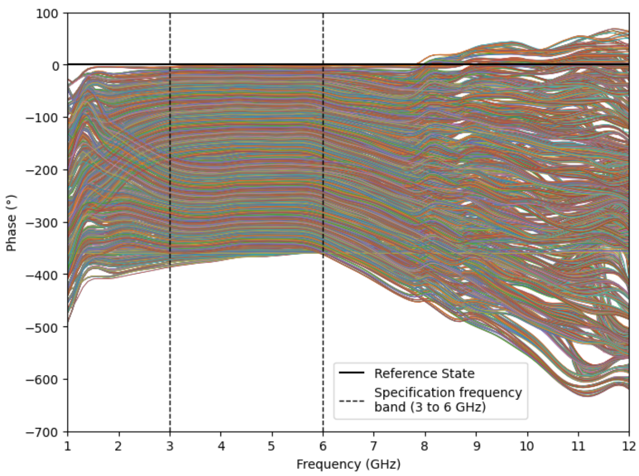
In Fig. 5 the gain and phase of the modules is shown relative to the nominal reference state (state 4032 - 0 dB attenuation, 0° phase shift). The gain range is close to the intended 32 dB across the specification frequency range, shown in Fig. 5a. This range increases at higher frequencies, but no large gaps are visible. Similarly, the phase shift is most consistent from 3-6 GHz. Gaps can be seen in Fig. 5b from 8 GHz. Multiple states begin to converge, reducing the total number of states possible, and the effective number of bits.

For readability, relative gain and phase plots across 64 states each are shown in Fig. 6; the reference 0° and 0 dB states are used respectively. The crossovers between states can be seen clearly in Fig. 6b between 2 and 3 GHz, though this does not result in many phase gaps. The normalised gain is more consistent than the phase, particularly outside the main frequency band.

The SPE is calculated for all frequencies, when the default control bits only are used to set the attenuation and phase shift for each state. The results at 3.3 GHz (lowest SPE_{RMS}) are shown in Fig. 7. The errors in the gain are shifted approximately 0.5 dB above the ideal levels. This is easy to adjust for, by changing the reference amplitude, but the phase shift error is much more significant. The phase is affected when the amplitude module attenuation is changed, resulting in a maximum phase error of close to -30°. The phase error is the reason for the poor SPE, which also worsens as the attenuation level increases, shown in Fig. 7c.

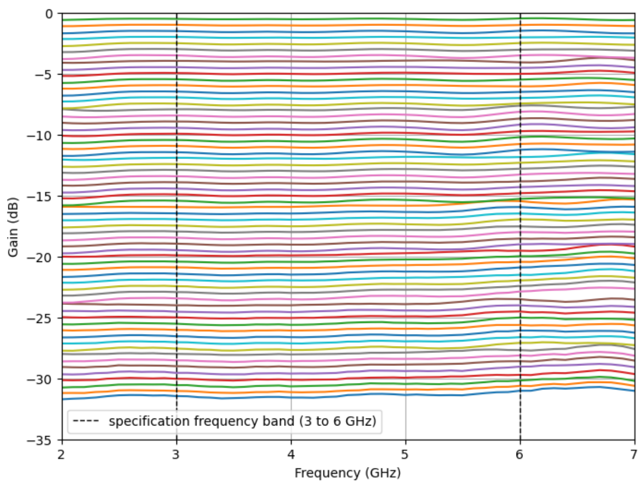


(a) Normalised Gain for all 4096 states

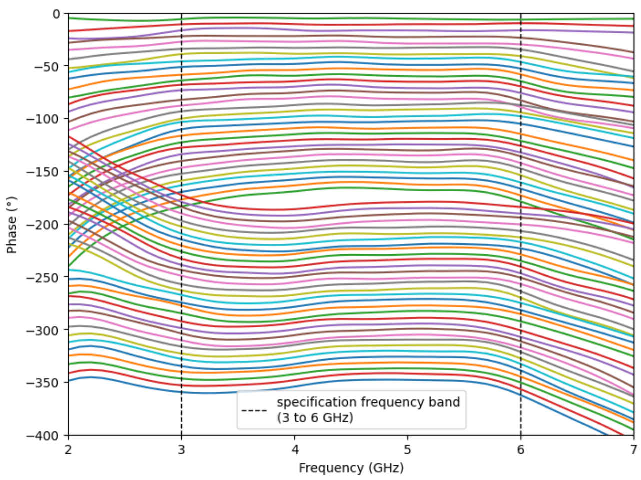


(b) Relative phase for all 4096 states

Fig. 5: Relative gain and phase of the combined modules across 4096 states, relative to the nominal 0 dB 0° state.



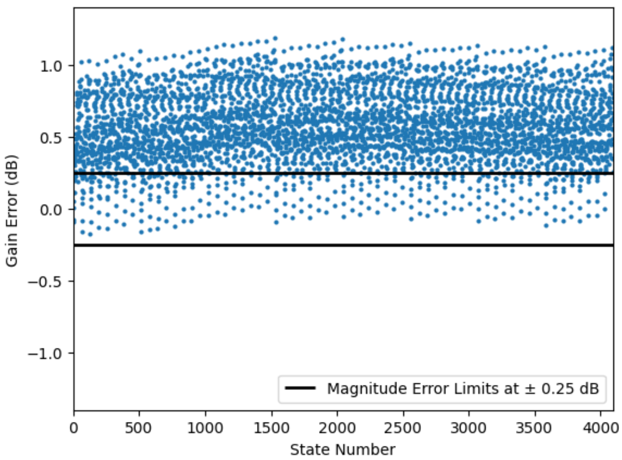
(a) Normalised gain for 0° phase state (across 64 states)



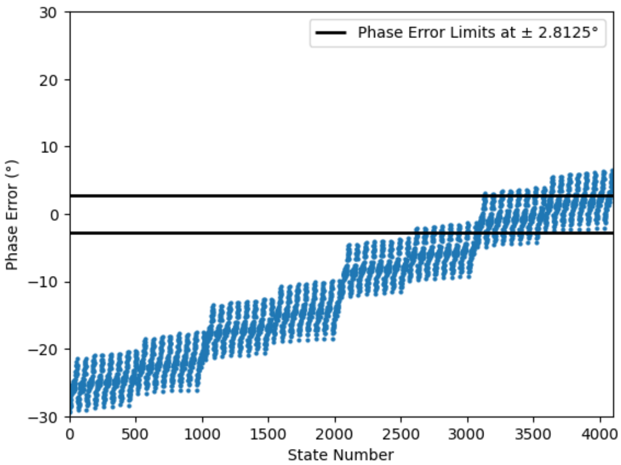
(b) Relative phase shift for 0 dB gain state (across 64 states)

Fig. 6: Relative gain and phase shifts of the combined modules across 64 states, relative to the nominal 0 dB 0° state.

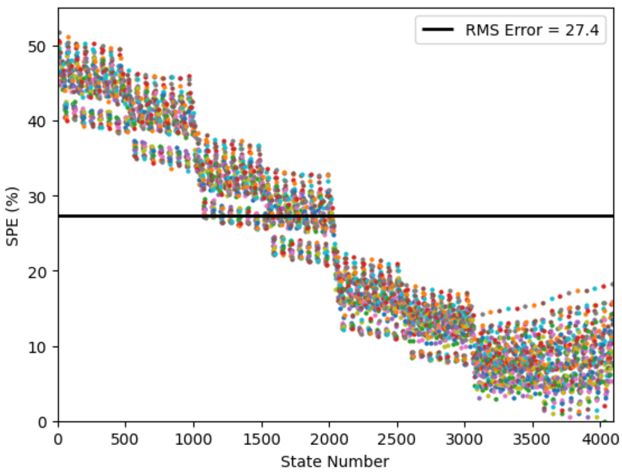
Clearly the cascade cannot be operated using the default states because the amplitude and phase modules are not phase- and gain-independent. Since the measured states cover the desired 32 dB 360° range, different states are available that are closer to most nominal states; these can be chosen to reduce the errors. To identify the optimal states, the SPE for each gain-phase state is calculated and compared against 2^{12} measured states, and the best state is selected. The optimal states are stored in a lookup table (Python dictionary) for each frequency. The improved errors using this approach are shown in Fig. 8.



(a) Gain Errors (default)

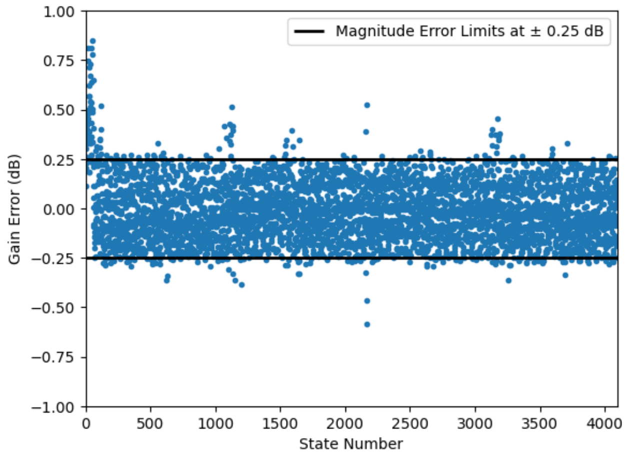


(b) Phase Errors (default)

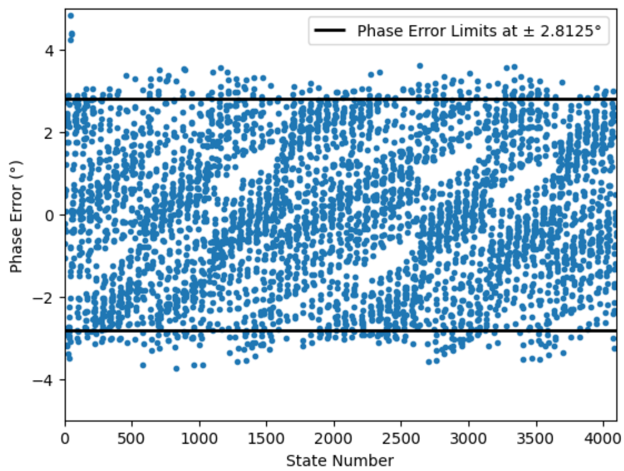


(c) SPE (default)

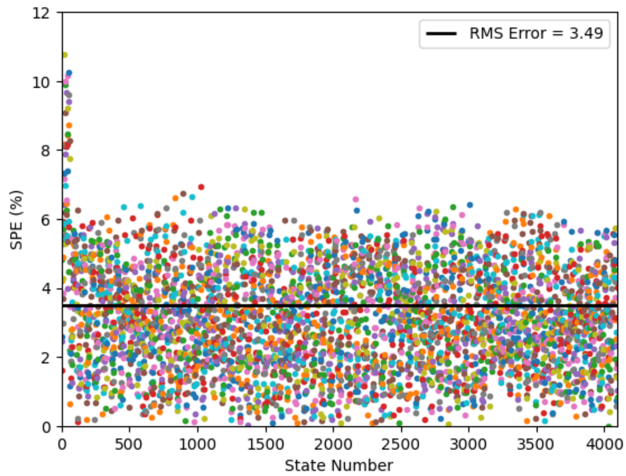
Fig. 7: Gain and phase errors and SPE across 4096 states, using default states only to calculate errors.



(a) Gain Errors (nearest)



(b) Phase Errors (nearest)



(c) SPE (nearest)

Fig. 8: Gain and phase errors, and SPE across 4096 states, using nearest states to calculate errors.

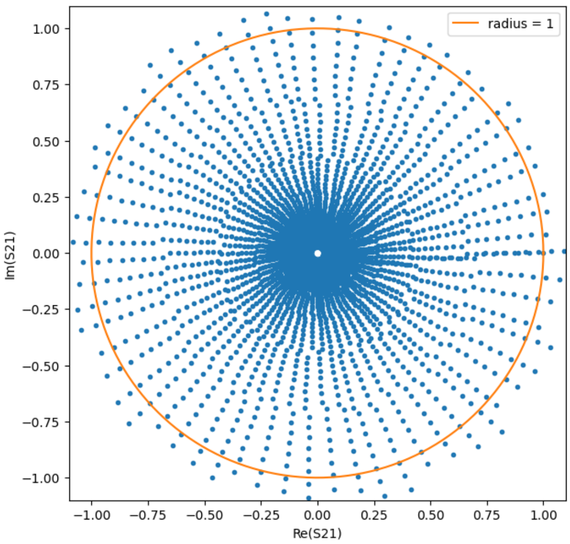


Fig. 9: S_{21} vectors, normalised to nominal 0 dB 0° state.

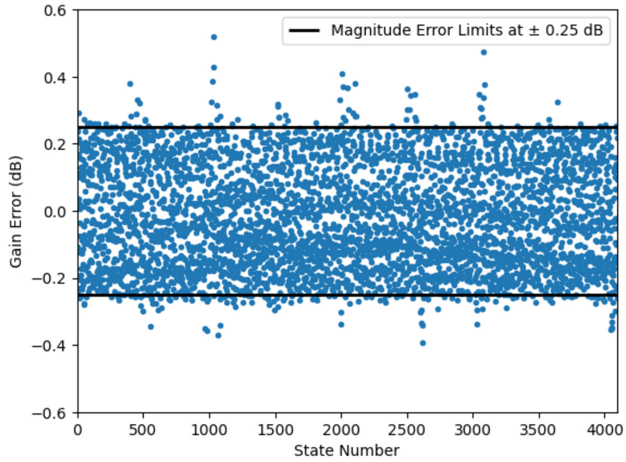
The magnitude errors in the maximum attenuation states are mostly greater than the tolerance. This is due to the amplitude of the nominal reference state 4032 used to normalise all the state amplitudes. There are 102 states with a greater amplitude than the nominal reference, which results in unused states at low attenuation levels and missing states at high attenuation levels (at the outer and inner regions respectively in Fig. 9). The state errors can be minimised by choosing a different reference point, with an amplitude close to the median of the nominal 0 dB states. The improvement in the gain errors and SPE are shown in Fig. 10.

At 3.3 GHz, most of the gain and phase errors are within their respective error tolerances (94.5% of gain errors and 93.7% of phase errors). The proportion of gain and phase errors within their tolerances as frequency varies is shown in Fig. 11. The maximum RMS gain and phase errors from 3-6 GHz are 0.19 dB and 1.86° respectively; their variation with frequency is shown in Fig. 12a. The SPE is lowest at 3.3 GHz (3.4%). The variations in SPE across states are shown in Fig. 10c, and the RMS SPE variation with frequency is shown in Fig. 12b.

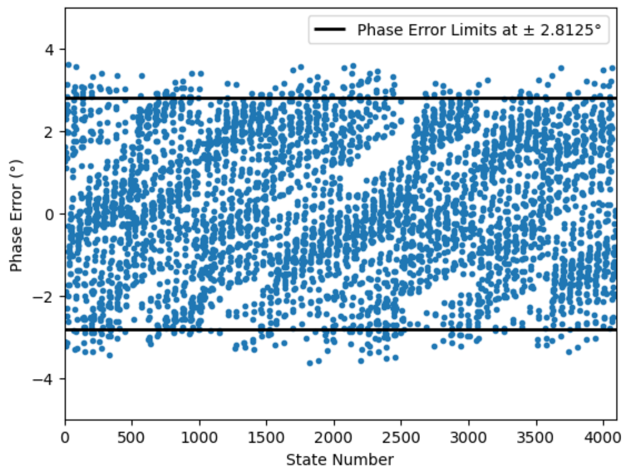
Rectangular and polar gain-phase plots are shown in Fig. 13. The polar plot (Fig. 13a) shows the rotation of the states with increasing attenuation; two points are marked on the plot with the same nominal phase (0°) but minimum and maximum attenuation levels respectively. The coverage of the full gain-phase space can be seen more clearly in Fig. 13b, where few points overlap.

V. Conclusions

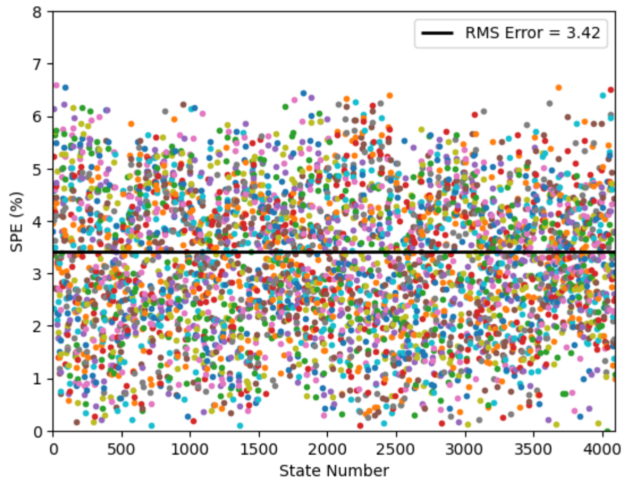
An automated test bench has been presented for the measurement and characterisation of 6-bit digital amplitude and phase modules. This approach can measure devices considerably faster than a manual approach, requiring no supervision. The performance of the devices was shown within and outside their intended operating frequencies, through RMS gain and phase errors, the relative magnitude of the state errors and the proportion of realisable states. The measured data was processed to generate an optimum look-up table, which achieves maximum RMS gain and phase errors of 0.19 dB and 1.86° respectively over the 3 to 6 GHz target operating band. Further work could incorporate EVM measurements into the test bench, and explore the performance of the modules with various modulation formats.



(a) Gain Errors (optimised)



(b) Phase Errors (optimised)



(c) SPE (optimised)

Fig. 10: Gain and phase errors, and SPE across 4096 states, using optimal states to calculate errors.

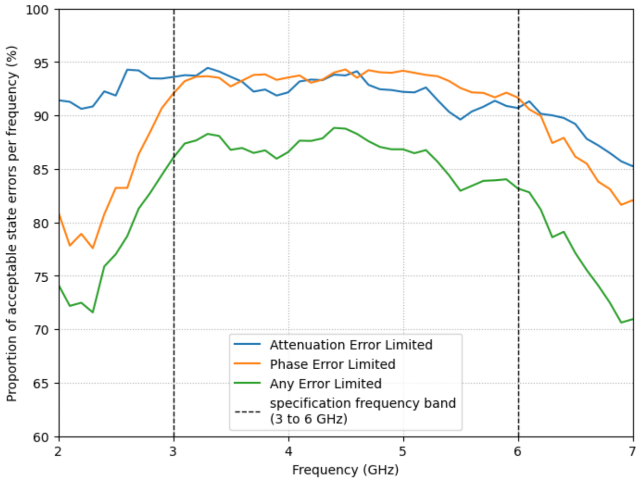
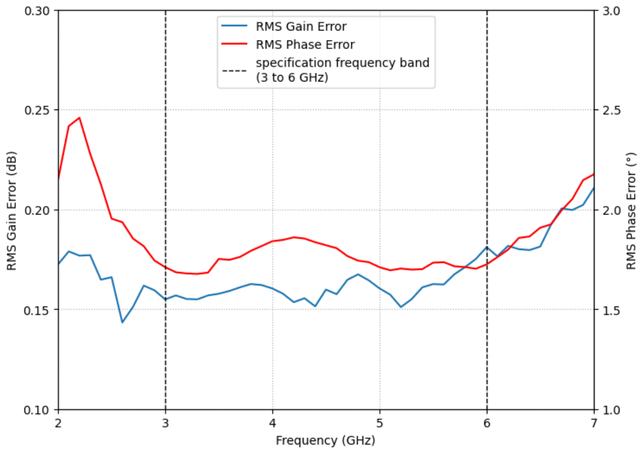
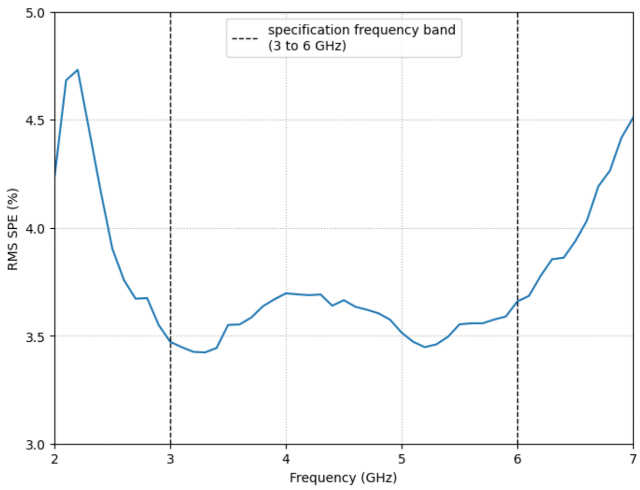


Fig. 11: Proportion of gain and phase errors within their tolerances.

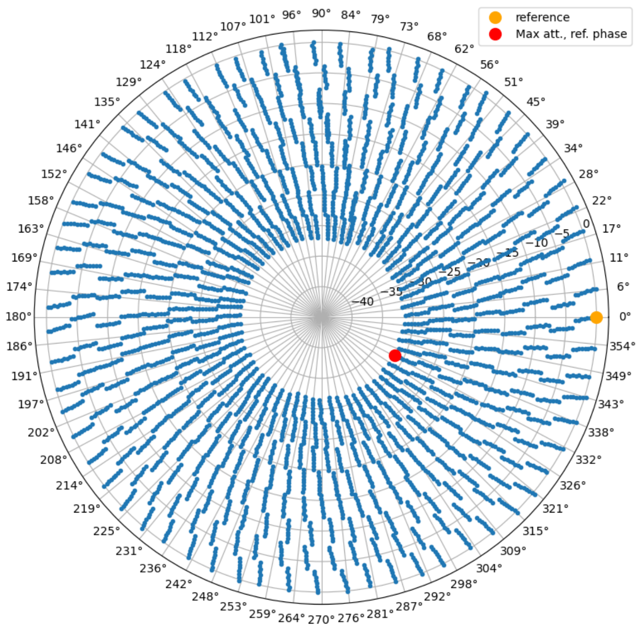


(a) RMS Gain and Phase Errors across 4096 states

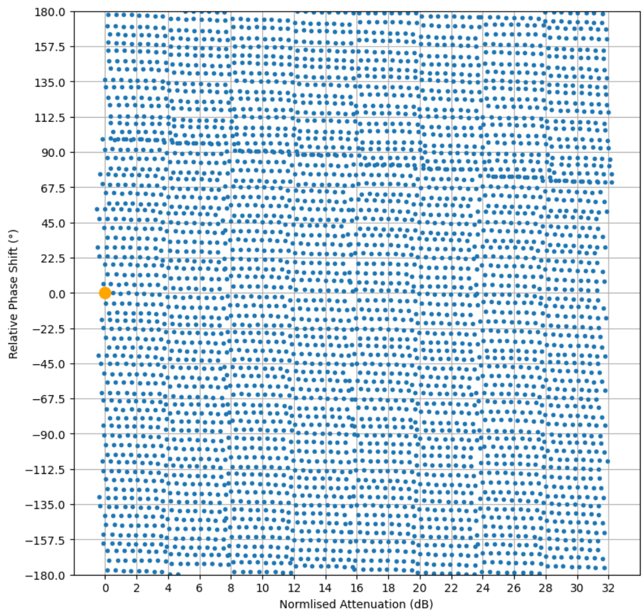


(b) RMS SPE across 4096 states

Fig. 12: RMS Gain Errors, Phase Errors and SPE across 4096 states.



(a) Polar



(b) Rectangular

Fig. 13: Normalised gain-phase plots, in dB