SECOND SOURCE POWER AMPLIFIER EVALUATION FOR PROPSIM CHANNEL EMULATOR

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Tässä kandidaatintyössä esitellään tehovahvistin Keysight Technologies PROPSIM F64 kanavaemulaattorin lähetinvastaanottimeen. Tehovahvistimen tärkeimmät ominaisuudet sekä suorituskyky, kuten taajuuskaistan tasaisuus, lineaarisuus ja virrankulutus, käydään läpi ja olemassaolevalle tehovahvistimelle evaluoidaan vaihtoehtoisia malleja. Pääsyy vaihtoehtoisen tehovahvistimen etsimiselle on nykyisen tehovahvistimen kalleus ja sen käyttämä kaksipuoleinen käyttöjännite, jonka toteutus nostaa osaltaan laitteen valmistuskustannuksia.

Tässä työssä tehovahvistimen tärkeimmäksi ominaisuudeksi määräytyy vasteen tasaisuus koko käytettävissä olevalla taajuusalueella. Johtuen piirilevytilan puutteesta, koko taajuusalue on katettava samalla vahvistimella. Myös vahvistimen lineaarisuuden, vahvistuksen ja virrankulutuksen vaikutusta kanavaemulaattorin suorituskykyyn analysoidaan työssä.

Evaluaation alussa tehovahvistinvaihtoehtoina on kolme erilaista vaihtoehtoa. Näistä ensimmäisen S-parametrit mitataan laboratoriossa evaluaatiolevyllä piirianalysaattorin avulla. Mittaustuloksista voidaan todeta, ettei ensimmäinen testattu vahvistinvaihtoehto yllä annettuihin spesifikaatioihin, varsinkaan taajuusvasteen yläpään osalta. Tästä johtuen tehovahvistimen biasoinnin vaikutusta taajuusvasteeseen analysoidaan toisena vaihtoehtona ja todetaan, että biasoinnilla on vaikutus sekä taajuuskaistan ala- että yläpäähän. Ensimmäisen vahvistimen taajuusvaste mitataan laajakaistaisella biaskelalla. Mittaustuloksista voidaan todeta, että vastetta ei saada riittävän hyväksi ainakaan yksinkertaisilla komponenttimuutoksilla.

Mittausten aikana testattavaksi saadaan uudeksi vaihtoehdoksi esituotantomalli tunnetun piirivalmistajan tehovahvistimesta. Tämän vahvistimen S-parametrit mitataan laboratoriossa ja sen todetaan olevan taajuusvasteeltaan, sovitukseltaan, virrankulutukseltaan, biasoinniltaan ja fyysiseltä kooltaan niin hyvä kompromissi, ettei jatkotutkimuksiin ole tarvetta käyttää enempää aikaa tässä vaiheessa.

Avainsanat: tehovahvistin, evaluaatiolevy, PROPSIM F64, biasointi, taajuusvasteen tasaisuus

ABSTRACT

In this thesis, a Power Amplifier (PA) for Keysight Technologies' PROPSIM F64 channel emulator transceiver is presented. The main characteristics and performance of a PA are examined and optional models for existing PA are evaluated. The main reason for an optional model is the cost and complexity of current PA with its two-sided bias voltage.

In this work, the most important characteristic of a PA is the gain flatness on the operating band. Since the printed circuit board space (PCB) is very limited, the whole frequency band must be taken care of with single PA. The relevance of linearity, gain and current consumption in channel emulator transceiver are also elaborated.

In the beginning of the evaluation, there were three suitable candidates for the PA. The S-parameters of first candidate were measured in laboratory on an evaluation board with a network analyzer. The measurements indicate that the upper frequency response is out of specifications. For the second option, the effect of bias inductor on the frequency response is analyzed. Since the biasing has an effect on the upper and lower ends of the response, a new measurement with a broadband inductor is carried out. Even with better biasing, the first PA variant cannot reach the specification, at least without further component tuning.

During the evaluation process, the hardware team received a preproduction model of a PA from a known semiconductor supplier to be tested as a new candidate. The S-parameters of this new variant are also measured and it is observed that this variant has such good frequency response, matching, current consumption biasing and physical size that there is no need for further evaluation at this point.

Key words: Power Amplifier, evaluation board, PROPSIM F64, bias inductor, gain flatness

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LIST OF ABBREVIATIONS AND SYMBOLS

5G NR	5G New Radio
ADC	Analog to digital converter
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BS	Base Station
CA	Carrier Aggregation
DAC	Digital to analog converter
dBm	Decibel milliwatts
DSP	digital signal processing
EoL	End-of-life
EVM	Error Vector Magnitude
FPGA	Field Programmable Gate Array
GUI	Graphical user interface
IF	Intermediate Frequency
IIP3	Input 3rd order Intercept Point
IM	Intermodulation
LO	Local Oscillator
MUX	Multiplex
MIMO	Multiple-Input Multiple-Output
NF	Noise Figure
OFDM	Orthogonal Frequency Division Multiplexing
OIP3	Output 3rd order Intercept Point
PA	Power Amplifier
PAPR	Peak to Average Power Ratio
PSD	Power Spectral Density
QAM	Quadrature Amplitude Modulation
RBW	Resolution Bandwidth
RF	Radio Frequency
RMS	Root Mean Square
Rx	Receiver
SNR, S/N	Signal to Noise Ratio
Tx	Transmitter
UMTS	Universal Mobile Telecommunications System
VSA	Vector Signal Analyzer
WCDMA	Wideband Code Division Multiple Access

1. INTRODUCTION

The high data rates and number of simultaneous users of modern communication systems, such as 5G new radio (5G NR) cause challenging engineering tasks for the designers of these systems. Since the capacity of a radio channel is proportional to signal to noise ratio (SNR) and available bandwidth, the communication systems move towards higher frequencies and wider spectrum as well as increasing number of transmit and receive antennas, i.e. multiple-input multiple-output (MIMO) schemes. These requirements for the modern communication systems naturally cause increasingly stringent requirements for the measurement equipment aimed to validate these devices and systems. During the development of a communication system, it is important to be able to simulate different approaches to the problem at hand. After the development of system or devices is finished, it is important to be able to validate their performance in possible working environments. One of the most important issues in validation of a wireless system is the system's behavior in a radio channel.

Radio channel is the main contributor of propagation challenges in any wireless communication system. These effects include slow and fast fading, delays, attenuation, noise, interference and Doppler shift. The effects of these phenomena have to be measured and studied in the development of wireless communication devices and systems. The need to simulate or emulate the impairments of radio channel in a laboratory environment stems from the cost and impracticality of carrying out these measurements in the field.

The testing of these modern systems or parts of them can be done in a simulator or with an emulator. The difference between these two is that a simulator is usually a computer program designed to imitate a real-world system to get information of its behavior with different inputs. For example, an electrical circuit simulator used to simulate a frequency response of a circuit with different component values. This type of program can be implemented with different programming languages and can run in different computer systems. A simulator typically aims to be easy and fast to use while sacrificing some amount of accuracy for this. An emulator on the other hand can be thought of as a platform consisting the hardware and software used to exactly replicate the behavior of another system. An emulator aims to substitute the system that it is emulating. For example, one existing solution for the emulation of radio channels is Keysight Technologies' Propsim channel emulator. Propsim (acronym for propagation simulator) offers the opportunity to mathematically model a multitude of wireless environment scenarios. These emulations mimic the radio channel phenomena according to standardized channel models. The emulations are carried out in baseband i.e. in digital domain with pre-defined emulation files. So the Propsim channel emulator consists of the hardware that is the platform on which the modeling software works and the actual modeling software. This thesis considers the hardware side of the emulator and more precisely the transceiver module. The transceiver module is responsible of transferring the signal between analog and digital domain, where the actual radio channel modeling occurs. More information of Propsim 5G channel emulation solution can be found in [1].

The purpose of this thesis is to examine and propose a variant for Propsim channel emulator transmitter power amplifier (PA). The current commercial channel emulator version PROPSIM F64 is specified for a frequency range of 500 MHz to 6 GHz with bandwidth of maximum 160 MHz for one channel unit. The peak output level is +5 dBm. The full unit consists of eight channel units, which in turn consist of eight transceivers each. The existing PA HMC465LP5 is able to deliver these specifications but the fact that there are 64 relatively costly custom made PAs in one full emulator, in addition to the reasons in the following make it beneficial to evaluate other variants.

The price and availability of components are often cause of concern in system development. After initial model, it is customary to examine the cost reduction aspect of chosen components. A second source or alternative supplier is also an important aspect in design since there can be problems with the supply of most popular components on the market or the lifetime of a component might come to end for unforeseen reasons. Therefore, the motivation for this thesis is partially the demand of a cost reduction model for future variants of the power amplifier and partially the aspect of component availability.

The rest of this thesis is organized as follows. In Chapter 2, Propsim channel emulator is presented and hardware configuration is described. Chapter 3 focuses on the requirements of a RF power amplifier and in Chapter 4 the measurement results are given for the tested power amplifiers.

2. PROPSIM CHANNEL EMULATOR

In this chapter the current model of Propsim channel emulator is introduced. Most important features are presented, while the focus is on the hardware side of the emulator.

2.1. PROPSIM F64

The current commercial model of Propsim emulator is named PROPSIM F64. As the name implies, it is equipped with 64 duplex radio channels and can be used to emulate aforementioned multipath channel effects through preconfigured software models, based on e.g. 3GPP standard models. A typical emulation case is the communication between user equipment (UE) and base station (BS). The front panel of PROPSIM F64 with its graphical user interface (GUI) is depicted in Figure 1. User signals are connected to the front panel connectors and emulation setup is controlled via GUI. A full description of Propsim emulator functionality is obviously beyond the scope of this thesis, but the principle of operation and transceiver hardware configuration is given next.

Figure 1. PROPSIM F64 and graphical user interface

2.2 Principle of hardware operation

In a modern wireless telecommunications system, the main signal processing is done in the baseband i.e. in the digital domain. This is true with Propsim channel emulator also. To get the digital data transmitted via an analog carrier or to get the incoming RF (Radio Frequency) signal down to baseband, a transceiver is needed. In Propsim, the transceiver consists the analog parts of receiver and transmitter between input/output ports and baseband parts. The generalized hardware operation of Propsim is thus that the receiver (Rx) adjusts the level of the incoming signal, that comes from front panel connectors via RF router module, and downconverts it to a baseband frequency for digital signal processing (DSP). The analog to digital converting (ADC) on the receiver chain for DSP as well as the digital to analog converting (DAC) on the transmitter chain are done in the baseband unit. The transceiver is a typical superheterodyne radio with two mixing stages, namely RF and IF (Intermediate Frequency) stages. The job of the transmitter chain is the opposite of the receiver, i.e. upconverting and adjusting the baseband signal to appropriate RF frequency and power level.

The two mixing stages consist of numerous switches, filters and amplifiers, responsible for the high/low band division as well as the up- and downconversion and level adjustment of input or output signals. In Propsim transceiver, the operating frequency range is from 500 MHz to 6 GHz. The RF and IF local oscillator (LO) signals used in mixing stages are generated in a separate local signal generator module. On the transmitter side of the transceiver, the last component before Rx/Tx separation is the power amplifier (PA). It is the final component in the analog chain responsible for mitigating the signal attenuation, stemming from mixer conversion losses and filter attenuation. In Propsim transceiver, the printed circuit board (PCB) space is very limited and therefore the use of an amplifier bank is not an option. This sets some strict requirements for the PA. These requirements and the function of the PA are elaborated next.

3. RF POWER AMPLIFIER

The task of a radio frequency power amplifier is to raise the signal to be transmitted to a specified level. This is done prior to the transmit antenna or as in Propsim prior to the Tx/Rx separation and output. The most important characteristics of a PA are power consumption, noise figure (NF) and linearity. The power consumption is very important in mobile devices, but since the 64 channel Propsim emulator has 64 power amplifiers along with a lot of power-hungry ADCs, DACs and FPGAs (Field Programmable Gate Arrays), all means to lower the current consumption need to be taken into consideration. NF on the other hand means the degradation of SNR due to noise added by the PA. This influences e.g. the calibration of Propsim channel unit. The linearity requirement means that the amplification needs to be done in a manner that does not cause interfering spurious artefacts in the transmission spectrum. The spurious components might reside outside of the system designated band or in the system channel, so they could interfere other wireless systems in the air interface, or in the case of channel emulation add non-realistic components to the current emulation.

In a transmitter, these components might arise from the suboptimalities of the PA such as nonlinear behaviour or be some LO feed-through which then get amplified by PA. Therefore, the power amplifier can be considered as the most critical part of any wireless transmitter that has to deal with modern digital modulation and multicarrier schemes. These signals may employ a bandwidth of hundreds of megahertz and fast changing envelope with high peak to average power ratio (PAPR) as in a popular orthogonal frequency division multiplexing (OFDM) systems [2, p.145-151].

3.1. PA requirements

There exists a multitude of general requirements for a PA, such as efficiency, linearity, gain flatness, bandwidth, size and cost. The determinative factor of linearity and efficiency of a PA is the operating class. Characteristics of different classes are elaborated in literature, such as [3] and are beyond the scope of this thesis, but it can be said that when dealing with linear amplifiers it is safe to think class A or AB amplifiers, so the efficiency is sacrificed for the sake of linearity. Linearity and efficiency are contradictory measures in that the highest linearity is achieved with the most inefficient classes.

In the context of channel emulator transmitter, the ruling constraints for a PA are gain flatness, linearity and size. The need for a flat gain arises from the wide frequency range of channel emulator and high bandwidths of modern communication systems e.g. carrier aggregation (CA) schemes. Because of the linearity constraint, the output 1 dB compression point should be as high as possible. As mentioned earlier, the high PAPR of OFDM causes additional constraints to PA output power and linearity. Since the PAPR can be 10 dB for OFDM, the PA needs to have a sufficient back-off margin. In channel emulation the PAPR translates to crest factor, which means the ratio of the peak RF power value to RMS (Root Mean Square) power [2, p.148]

The size constraint on the other hand limits the available choices to more integrated solutions, of which the most common and easy to use is the gain block amplifier. The gain blocks generally offer good internal matching, good isolation and easy biasing. These are often broadband general-purpose amplifiers with medium gain and are easily prototyped with evaluation board as elaborated later in this thesis. A description of gain block amplifiers can be found in [4**]**. The specifications for the evaluation variants are listed in Table 1. These specifications are based on the current PA HMC465LP5. As stated earlier, this PA is custom made to Propsim specifications (which does not mean that it is not commercially available to other customers) and with two-sided biasing makes it a somewhat complex and costly component. Its data sheet can be found in [5].

Table 1. Power Amplifier Specifications

Frequency range	500 MHz - 6 GHz
Gain	> 15 dB
Gain flatness	+- 1 dB max
Input matching	< -15 dB
Output matching	< -15 dB
Noise figure	< 4 dB
Output 1dB compression point	> + 23 dB
Output 3rd order intercept	> + 32 dB
Power supply	+5V / max 160 mA

3.2. PA Variants

At the beginning of this evaluation, there were multitude of different PAs on the market, but only a few of them showed the wideband gain flatness needed in channel emulator transceiver. Some examples are Qorvo's SBB4089Z, Mini-Circuits' CMA-62+ and ASB's AWG 3020. The one that looked most promising, was readily available and had a price perk was AWG 3020, data sheet in [5], so this PA was chosen to be evaluated first.

4. EVALUATION BOARD MEASUREMENTS

Choosing a component or evaluating variants for a design usually begins with going through the vendor data sheets. This data offers the designer a laboratory tested description of the performance of the component in question. The conditions in the vendor laboratory, where the data sheet measurements are done, might not be same as the conditions in the final design. Best prototyping results could be achieved with testing the components in the final PCB, but since this is not usually possible, the non-idealities of e.g. the biasing and matching networks can be tested in laboratory with evaluation board measurements. Most vendors offer evaluation boards for their PAs or gain blocks to support design prototyping. With these boards it is relatively easy for example to measure the effects of different biasing circuitry. One such evaluation board is visible in Figure 2. where the AWG 3020 amplifier on an evaluation board is presented. The component listing can be found in the data sheet [6].

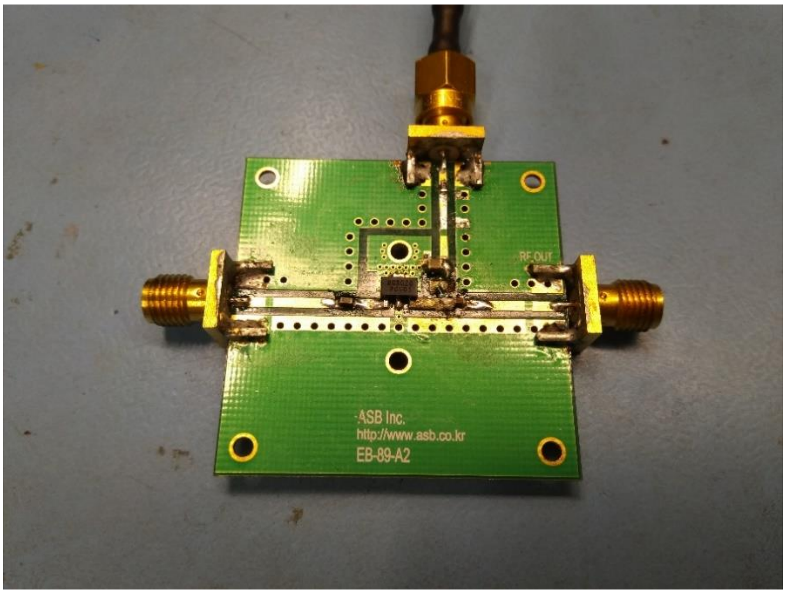

Figure 2. AWG 3020 evaluation board setup

4.1. AWG 3020 Power Amplifier

Using the evaluation board together with a voltage source and a network analyzer, the AWG 3020 PA was tested. The PA draws 100 mA of current with 5V bias voltage. The S-parameters can be seen in Figure 3. It is evident from the measurements that the higher end of frequency response does not meet the flatness specifications. This behavior arises from the biasing network of the PA and is considered in detail next. It seems also that there might be some work to be done with the matching department, as can be seen in the S11 and S22 measurements. Whether this is due to some effect of the evaluation board connection or something else, would call for further investigations and component tuning.

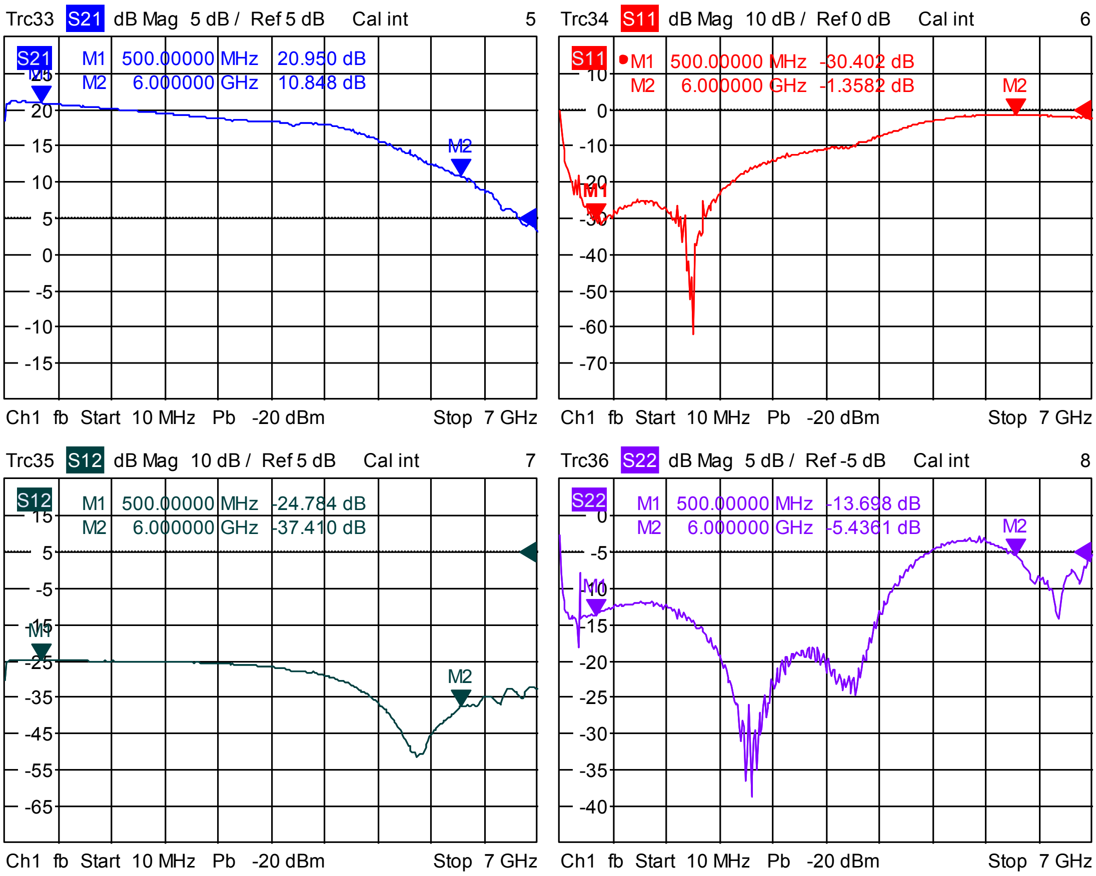

Figure 3. S-parameters of AWG 3020 with regular bias inductor

4.2 Effect of RF choke on usable gain bandwidth

Since the gain flatness of the AWB 3020 does not meet the specifications, it is beneficial at this point to take look a little bit deeper into the effect of PA biasing network. Biasing network's role is to provide DC current for the operation of the PA. This requires an inductor in series to prevent the RF signal leaking into the current supply. The bias inductor has impact on the lower and higher end of the frequency response; bias inductor should pass DC current and block everything else. To allow low frequency signals through PA, a high inductance value in the bias network is needed. In practice, this means an inductance around 1 uH. The inductor's series resonant frequency influences the higher frequency range. On a traditional chip inductor, the self-resonant frequency decreases with increasing inductance. This causes the higher frequencies in the amplified spectrum to attenuate, since the inductors electrical behaviour is now more capacitive than inductive [7].

RF choke is an inductor consisting of thin wire wound around a ferrite core. One example is Mini-Circuits TCCH-80+, data sheet in [8] and visible in Figure 4. With a wideband RF choke, the usable frequency range is larger than with a traditional inductor [9]. This comes with the price of reduced size-efficiency and more difficult assembly and handling. AWG 3020 S-parameter measurement with broadband bias inductor can be seen in Figure 5. From the S21 figure it can be seen that the response is a little bit better on the 6 GHz region (note the different scaling than in previous figure). Unfortunately, this evaluation board is not suitable for this type of inductor, so there is some ripple in the response. The S-parameter measurement demonstrates that even with better inductor, this PA cannot meet the higher frequency specification of gain level and flatness without additional tuning work, so the evaluation should continue to next variant.

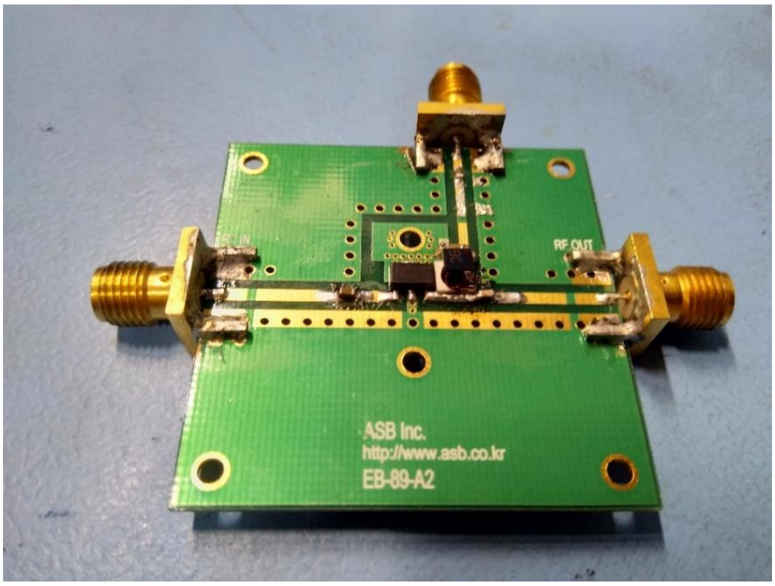

Figure 4. AWG 3020 with TCCH-80+ RF choke

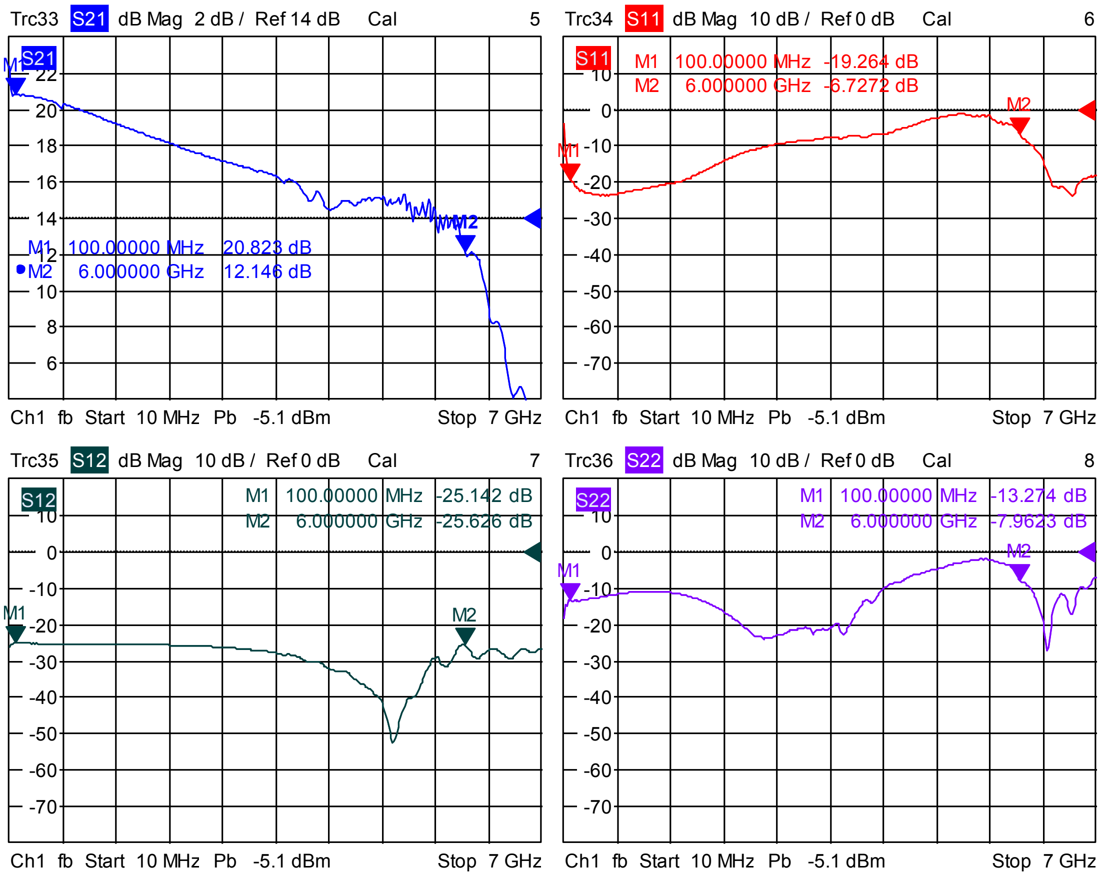

Figure 5. Broadband inductor’s impact on frequency response with AWG 3020

4.2 Custom amplifier

Before starting this evaluation, a well-known semiconductor vendor was asked to study the possibility to manufacture or customize a simplified version of their design based on the needs of Keysight Oulu R&D for Propsim channel emulator. Although it was earlier mentioned that the component selection begins with going through the vendor data sheets, it is also possible that the company has enough relevance or leverage in the field, that the vendor(s) have interest in individual design according to the customers specifications. This was the case with the current PA, and this was the case here also. Since the Propsim R&D department has had a long co-operation with some major suppliers, it was possible to request this solution. The pre-release of a custom PA was completed during this evaluation report. Since this PA is at an early stage of development, the data sheet is not commonly available at the writing of this, but the evaluation board can be seen in Figure 6. Although the model has to be blurred for this pre-release design, it is evident that the size and simpler biasing network specification are fulfilled with this model. This PA is biased with one sided voltage of +5V and draws 60 mA current, so the current consumption is also at a good level.

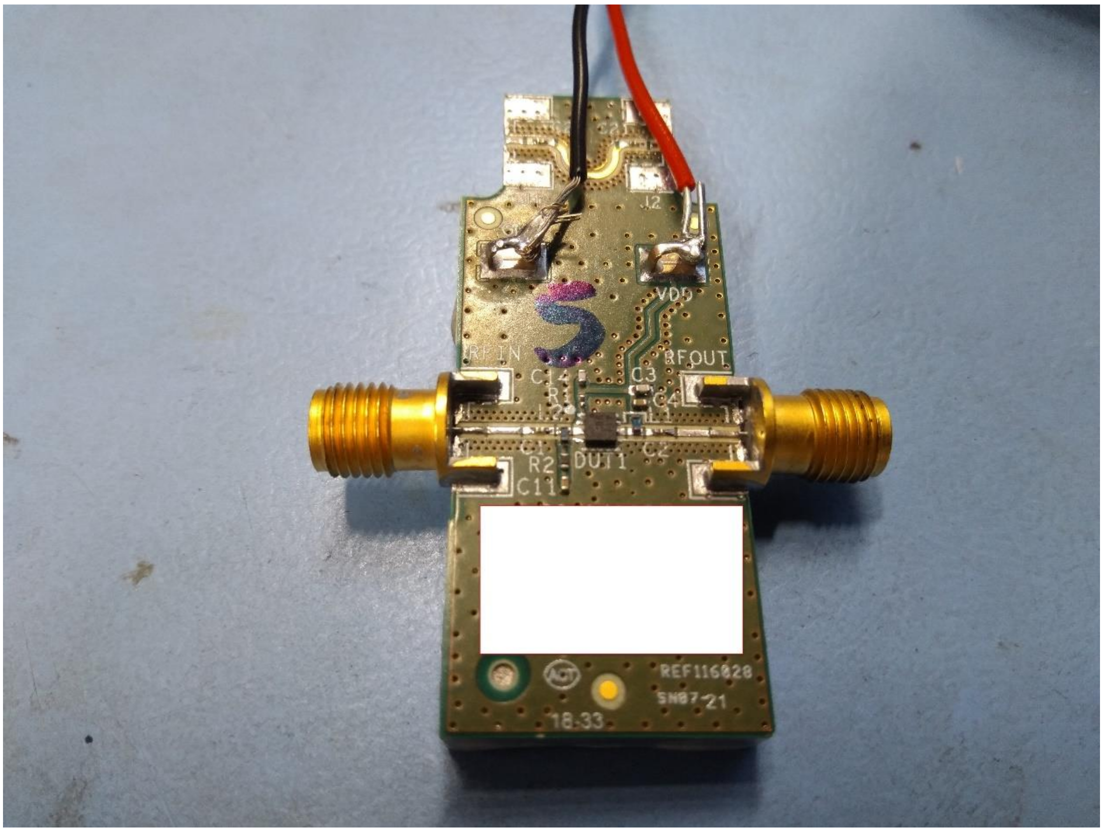

Figure 6. Evaluation board of new custom amplifier

The S-parameters for the final variant can be seen if Figure 7. It is clear that the gain flatness is much better than with AWG 3020, although the gain level is not quite in original specification. The other constraints, such as the size, current consumption, matching (S11 and S22) and isolation (S12) of this PA are at such a good level that further investigations for a PA variant are not necessary at this time.

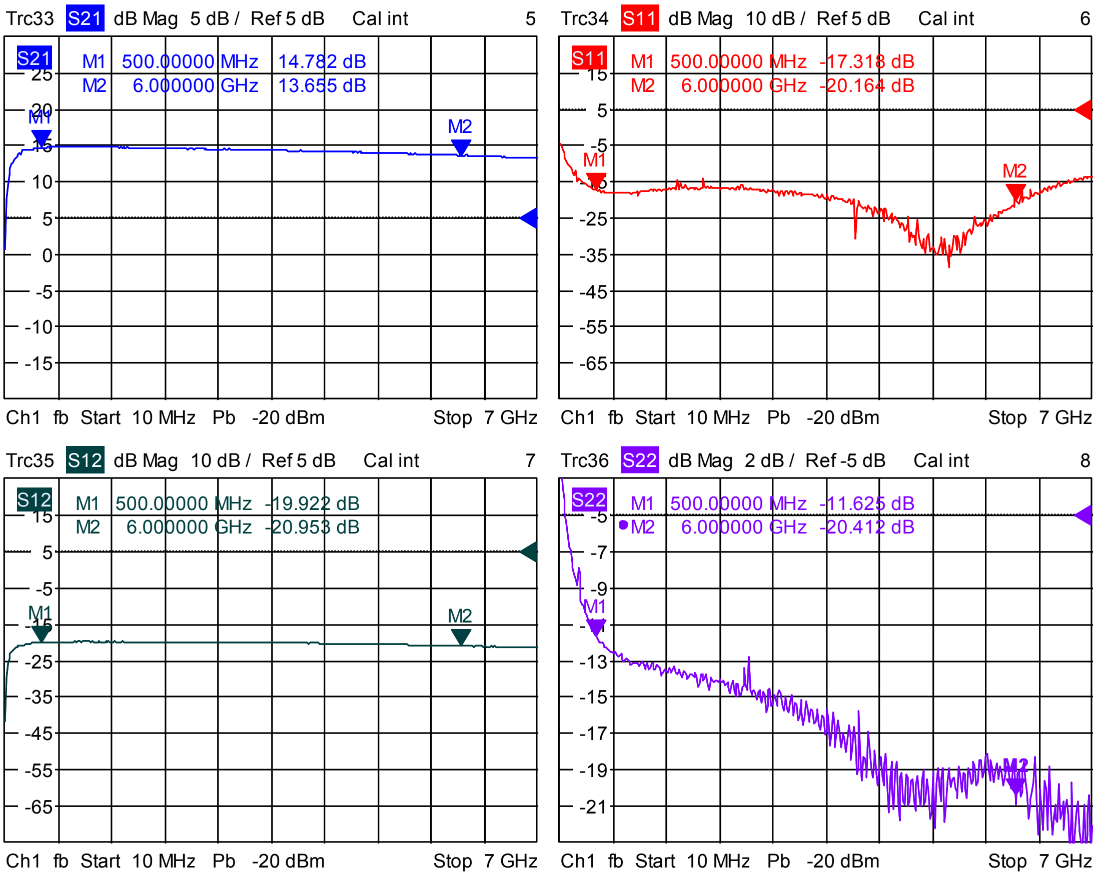

Figure 7. S-parameters of custom amplifier

4. CONCLUSIONS

In this thesis an evaluation of a second source power amplifier for Propsim channel emulator transceiver is presented. The need for such a variant is explained in the introductory section. The process consists of defining the specifications for the PA variant, performing laboratory measurements for the chosen variant and analyzing the results. The importance and effect of biasing network on the gain flatness and broadness of frequency range is also elaborated.

It is found out that the first chosen PA variant cannot meet the frequency flatness specification. This PA is also tested with a broadband RF choke, but the upper end of the frequency response is still out of specification. This variant is not suitable option without further circuit tuning. Since one objective of this evaluation was to find a simple solution as fast as possible, the aforementioned tuning or adjusting is not done. During the evaluation process the hardware team received a newly built pre-production model PA from a known semi-conductor vendor. Since this is not yet a commercial model, it is only possible to introduce here a rough description of the performance of this PA. Based on the S-parameter measurements, current consumption, size and simpler model than the current one, this PA is chosen as the second source variant.

For future evaluations, it can be said that checking the performance found in data sheet against the real performance on an evaluation board is a valuable method to ensure the operation of chosen component. Given more time and component resources, it would be possible to further tune the PA circuits, and the number of alternatives would be higher. Since these two assets seem to always be the most stringent constraints in a commercial design work, a laboratory measurement with evaluation board is a quick and worthy compromise. Although the process did not go quite as expected in the beginning, which is not uncommon in commercial design work, a second source PA for Propsim transceiver was found.

5. REFERENCES

[1] PROPSIM F64 5G Channel Emulation solution F8800A - https://literature.cdn.keysight.com/litweb/pdf/5992-2962EN.pdf?id=2970742; accessed in 5.5.2019

[2] Luzzatto A., Haridim M. (2017) Wireless Transceiver Design 2nd edition

[3] https://www.electronics-tutorials.ws/amplifier/amplifier-classes.html; accessed in5.5.2019

[4] http://www.richardsonrfpd.com/Pages/Product-End-Category.aspx?productCategory=10039; accessed in 5.5.2019

[5] https://www.analog.com/media/en/technical-documentation/data-sheets/hmc465.pdf; accessed in 19.3.2019

[6] https://www.asb.co.kr/datasheet/AWG3020.pdf; accessed in 5.5.2019

[7] RF components and measurements course material - 3.2. Inductors

[8] https://www.minicircuits.com/pdfs/TCCH-80+.pdf; accessed in 19.3.2019

[9] https://www.minicircuits.com/app/AN60-010.pdf; accessed in 19.3.2019