Uncertainties in small-signal and large-signal measurements of RF amplifiers using a VNA

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Uncertainties in typical small-signal and large-signal amplifier parameters measured using a vector network analyzer (VNA) are investigated in this paper. Methods to evaluate the measurement uncertainty in return losses, input power, output power, power gain, 1 dB compression point, etc, based on the use of the VNA dynamic uncertainty option (VNA-DUO) software tool from Keysight Technologies are applied to a commercial amplifier between 0.5 GHz and 8 GHz.

INTRODUCTION

Amplifiers are used to magnify signals to prevent them from being obscured by noise. Amplifiers find applications throughout electronics but, in this paper, we focus on radio frequency (RF) amplifiers i.e. those operating in the frequency range 100 MHz to 100 GHz [1]. An amplifier responds linearly to a small input signal but can show non-linear behavior, such as gain compression and harmonic generation, when the amplitude of the input signal becomes sufficiently large [2]. The characterization of an amplifier under different operating conditions is essential for designers and users of the amplifier. The small-signal response of RF amplifiers is characterized by their reflection and transmission coefficients i.e. by their scattering parameters (S-parameters) [3]. Other parameters (such as saturated output power, large-signal gain, 1 dB gain compression point, efficiency, measures of harmonic distortion, and measures of two-tone intermodulation distortion etc.) are required to characterize the large-signal, non-linear, response of the amplifier [2, 3]. The S-parameters of an amplifier vary with frequency but, due to linearity, are independent of the power of the input signal. However, the large-signal response of an amplifier, due to non-linearity, depends on both the frequency and the power level of the input signal.

One of the main instruments used to characterize the electrical performance of an amplifier is a vector network analyzer (VNA), which can measure S-parameters, power, and noise figure (NF) amongst other parameters [3]. Imperfections in the VNA measurement setup can be largely corrected by calibration [4].

In order to have confidence in the result of a measurement, and when comparing it with the results of other measurements, it is important to know the uncertainty in the measurement. Documents providing guidance on the evaluation of measurement uncertainty, in general, include [5, 6, 7] whilst information specific to the evaluation of the uncertainty in RF measurements is given in [8, 9]. In this paper, we have used the VNA dynamic uncertainty option (VNA-DUO) software tool from Keysight Technologies [10] to evaluate the measurement uncertainty in some fundamental parameters of an amplifier. Both small-signal and large-signal parameters of an amplifier are considered.

To evaluate the measurement uncertainty in S-parameters at RF frequencies, software tools such as VNA Tools [11], MUF [12], PIMMS [13], and FAME [14] are used at National Metrology Institutes (NMIs) around the world. VNA-DUO can evaluate the measurement uncertainty in S-parameters and power in real-time once the sources of uncertainty in the VNA and power meter have been fully characterized. The measurement uncertainties are evaluated within the VNA and are displayed as error bars or elliptical uncertainty regions on the VNA screen. VNA-DUO has recently been commissioned for use at the UK's National Physical Laboratory (NPL) [15].

An amplifier's small-signal parameters (which characterize its linear behavior in response to a small-signal stimulus) such as input return loss, output return loss, small-signal gain, and

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reverse isolation are determined from its S-parameters. The uncertainties in these small-signal parameters can be determined from the uncertainties in the S-parameters. The S-parameter uncertainty due to connector repeatability, cable flexing, noise floor, trace noise, etc is evaluated in VNA-DUO by the analysis of series of observations (type A evaluation) and the uncertainty due to the calibration standards etc is evaluated by other means (type B evaluation). The S-parameters are based on ratios between the incident and scattered waves at the ports of the amplifier and are independent of the incident power level and do not require an absolute power calibration of the VNA.

On the other hand, an amplifier's large-signal parameters (which characterize its non-linear behavior in response to a large-signal stimulus) such as output power, power gain (G_P), saturated output power (P_{sat}), 1 dB compression point (P_{1dB}), etc, depending on the power in the incident and scattered waves. Measurement of the incident and scattered power requires an absolute calibration of the VNA using a power meter in addition to the usual S-parameter (vector) calibration of the VNA. VNA-DUO evaluates the uncertainty in the VNA power measurement from the uncertainty in the power meter reading as well as the uncertainty due to systematic and random effects in the VNA.

UNCERTAINTIES IN AMPLIFIER PARAMETERS

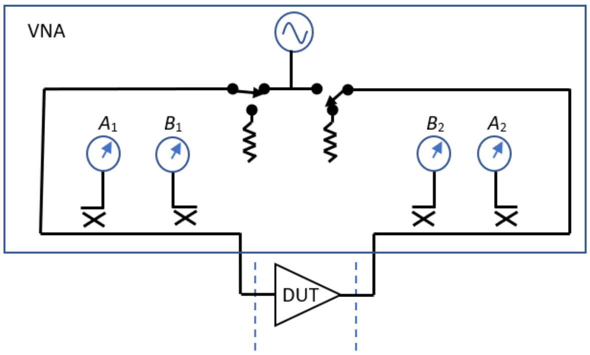
An active RF device such as an amplifier responds linearly to sufficiently small input signals. In this case, the output signal is proportional to the input signal and the output power is much smaller than the saturated output power, P_{sat}, of the amplifier. The small-signal performance of RF amplifiers is usually characterized using a VNA which measures the complex-valued S-parameters of the amplifier – i.e. the magnitudes and phases of its reflection and transmission coefficients. Fig 1 shows a typical block diagram of a 2 port VNA for measurement of a 2-port device under test (DUT). To minimize systematic errors, the VNA is calibrated using an S-parameter (vector) calibration such as Thru-reflect-line (TRL), short-open-load-thru (SOLT), etc. For larger input signals, the amplifier responds non-linearly i.e. the output power is not proportional to the input power. In this case, S-parameters alone do not fully describe the amplifier behavior. To measure large-signal amplifier behavior, the VNA requires an additional power calibration. The uncertainties in small-signal and large-signal amplifier parameters are discussed below.

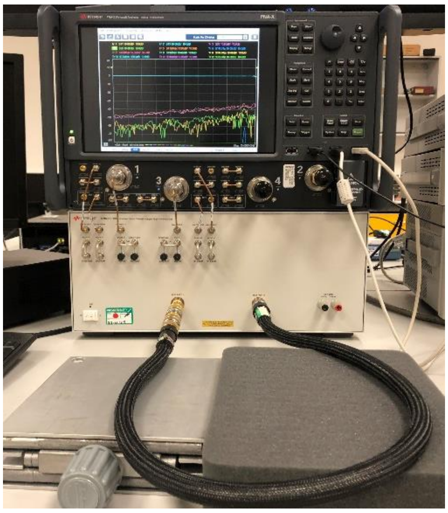
Uncertainties in small-signal amplifier parameters

The amplifier operating in linear mode can be evaluated with S-parameter measurements. However, for evaluation of the measurement uncertainty, the methods used in [10] - [13] can fail when the parameters of the DUT can change due to DC supply, thermal self-heating, changes in active junction regions, electromagnetic influence due to proximity, environmental changes, etc. Tools such as VNA-DUO which are pre-characterized for uncertainty are more suitable for such measurements. For S-parameter measurements, VNA-DUO considers three sources of uncertainty [15]: (i) noise in the VNA (noise floor and trace noise); (ii) cable and connector repeatability; and (iii) the calibration kit. These sources of uncertainty are characterized before the measurement of the DUT and then the corrected S-parameters of the DUT together with their uncertainties are evaluated and displayed on the VNA screen in real-time. A detailed study of VNA-DUO has been reported in [15]. Small-signal amplifier parameters, such as the input and output return losses, small-signal gain, and reverse isolation, together with their uncertainties can be measured using VNA-DUO.

Uncertainties in large-signal amplifier parameters

Some large-signal characteristics of an amplifier such as G_p, P_{1dB}, and gain compression can be measured using a VNA but this requires a power calibration of the VNA with a power meter. To determine the uncertainties in the subsequent measurements, the uncertainties associated with the power meter must also be known. VNA-DUO enables the uncertainties in the power meter and the uncertainties in the S-parameters to be propagated to the VNA receiver measurements. From the measured receiver powers and their uncertainties, the amplifier's other parameters can be fully determined, and the associated uncertainties can be evaluated. Methods to evaluate the uncertainties in some large-signal parameters are explained in the section entitled "the evaluation of uncertainty".





(a) (b)

Fig. 1. (a) A 2 port VNA block diagram showing the four receivers, A_1, B_1, A_2, and B_2. (b) photograph of the measurement setup.

VNA-DUO uncertainty evaluation tool

VNA-DUO considers the following four sources of uncertainty for S-parameters and power measured using a VNA:

1) Uncertainty due to the definition of the calibration standards. The uncertainty can be based on fully characterised calibration standards, mechanical tolerances or on polynomial based models. Some manufacturers provide an uncertainty characterization of some of their calibration kits.
2) Uncertainty due to electrical noise in the VNA. This source of uncertainty is characterized by repeat measurements (typically 20 repeats) of both a well-matched standard and a high reflect standard made on each port of the VNA. The standards are not disconnected from the VNA between measurements.
3) Uncertainty due to cable flexing and connector repeatability. This source of uncertainty is characterized by repeat measurements (typically 20 repeats) of both a well-matched standard and a high reflect standard made on each port of the VNA. The flexible RF cable (if present) is moved and the standards are disconnected from the VNA and reconnected with a different orientation between measurements.
4) Uncertainty in the power meter used in the power calibration of the VNA.

Once these sources of uncertainty have been characterised, VNA-DUO propagates the uncertainties to S-parameters and power measured by the VNA. The sources of uncertainty in various amplifier parameters measured on a VNA and their relative importance are indicated in Table 1.

Table 1. Uncertainty contributions considered in the measurement of various amplifier parameters using a VNA. The numbers indicate the relative size of each contribution for each parameter with (1) denoting the largest contribution.

Uncertainty contributions	Amplifier parameters				
	S-parameters	Input Power	Output Power	Power Gain	Gain Compression
Power Meter	✗	✓ (1)	✓ (1)	✓ (1)	✓ (1)
Calibration Standards	✓ (1)	✓ (2)	✓ (2)	✓ (2)	✓ (2)
Connector Repeatability	✓ (2)	✓ (3)	✓ (3)	✓ (3)	✓ (3)
Electrical Noise	✓ (3)	✓ (4)	✓ (4)	✓ (4)	✓ (4)

EVALUATION OF UNCERTAINTIES

The power gain, G_{P}, of an amplifier excited at port 1 is defined as the ratio of the output power (i.e. power delivered to the load), P_{L}, to the input power (i.e. power accepted at the input to the amplifier), P_{IN}. It can be calculated from the measured incident and scattered waves using (1).

$$G_{\mathrm{P}} = \frac{P_{\mathrm{L}}}{P_{\mathrm{IN}}} = \frac{|B_2|^2 - |A_2|^2}{|A_1|^2 - |B_1|^2} \tag{1}$$

where A_1 and B_1 are, respectively, the complex-valued incident and scattered wave amplitudes at port 1 of the amplifier and A_2 and B_2 are the corresponding quantities at port 2. For an amplifier terminated with a matched load, $|A_2| = 0$, and so (1) becomes:

$$G_{\mathrm{P}} = \frac{|B_2|^2}{|A_1|^2 - |B_1|^2} \tag{2}$$

Henceforth, in this paper, only the power gain into a matched load will be considered.

The uncertainty in the input power ($u(P_{\mathrm{IN}})$) and in the power gain ($u(G_{\mathrm{P}})$) are calculated from the uncertainties in the linear magnitudes of the incident and scattered waves ($u(|A_1|)$, ($u(|B_1|)$, and $u(|B_2|)$) using the law of propagation of uncertainty (LPU) as:

$$u(P_{\mathrm{IN}}) = \sqrt{4(|A_1|^2 u^2(|A_1|) + |B_1|^2 u^2(|B_1|))} \tag{3}$$

$$u(G_{\mathrm{P}}) = \sqrt{\frac{4G_{\mathrm{P}}}{P_{\mathrm{IN}}}\left(u^2(|\mathrm{B}_2|) + \frac{G_P|A_1|^2}{P_{IN}} u^2(|A_1|) + \frac{G_P|B_1|^2}{P_{IN}} u^2(|\mathrm{B}_1|)\right)} \tag{4}$$

The 1 dB compression point of an amplifier ($P_{1\mathrm{dB}}$) is defined to be the linear output power from the amplifier when its gain is reduced by 1 dB (i.e. by a factor of 1.2589) from its linear small-signal gain (G_{ss}) and is expressed as:

$$P_{1\mathrm{dB}} = \frac{G_{\mathrm{ss}} P_{\mathrm{IN\ 1dB}}}{1.2589} \tag{5}$$

where $P_{\mathrm{IN\ 1dB}}$ is the linear input power corresponding to the output power $P_{1\mathrm{dB}}$.

The relative uncertainty in linear P_{1dB} ($u(P_{1\mathrm{dB}})/P_{1\mathrm{dB}}$) is calculated by adding in quadrature the relative uncertainty in G_{ss} ($u(G_{\mathrm{ss}})\,/G_{\mathrm{P0}}$) and the relative uncertainty in $P_{\mathrm{IN\ 1dB}}$ ($u(P_{\mathrm{IN\ 1dB}})/P_{\mathrm{IN\ 1dB}}$) as follows:

$$u(P_{1\mathrm{dB}}) = P_{1\mathrm{dB}}\sqrt{\left(\left(\frac{u(G_{\mathrm{ss}})}{G_{\mathrm{ss}}}\right)^2 + \left(\frac{u(P_{\mathrm{IN\ 1dB}})}{P_{\mathrm{IN\ 1dB}}}\right)^2\right)} \quad (6)$$

To calculate the uncertainty in a logrithmic quantity (i.e. a quantity expressed in dB) given the uncertainty in the corresponding linear quantity, the nominal linear value and the maximum linear value (i.e. nominal value + uncertainty) were converted to dB and the difference in those dB values was used as the uncertainty expressed in dB.

EXPERIMENTAL DETAILS

Measurements were made using VNA-DUO installed on a Keysight N5247B PNA-X VNA and a high-power test-set (U3020B) as shown in Fig. 1(b). The high-power test-set consists of four low-loss 20 dB directional couplers. To keep the measurements signal levels within the linear region of the VNA receivers, additional 10 dB attenuators on the port 1 receivers and 20 dB attenuators on the port 2 receivers were used. The connections between the VNA and the high-power test set were made using semi-rigid coaxial cables. Port 1 of the test set was connected to the DUT with a fixed 3.5 mm ruggedized RF adapter and Port 2 of the test set was connected to the DUT with a flexible test port extension cable.

For small-signal characterization of the amplifier, S-parameters with uncertainty were measured using the VNA with the following settings:

- Frequency: 100 MHz to 8 GHz
- Frequency step: 50 MHz
- Power: -5 dBm
- IF Bandwidth: 10 Hz

The first step was to characterise the sources of uncertainty in the measurement as described in the Section entitled "VNA-DUO uncertainty evaluation tool". The VNA was calibrated using a mechanical calibration kit with a firmware short-open-load-reciprocal (SOLR) calibration. A mechanical calibration kit (Keysight 85052D) which had previously been characterized for uncertainty using NPL's primary impedance microwave measurement system (PIMMS) was used for calibration.

In our experiment, the four sources of uncertainty were characterized as follows:

1) The uncertainty due to the calibration standards was based on the characterization of the calibration standards at NPL using PIMMS.
2) Uncertainty due to electrical noise was accounted for by 20 repeat measurements of a match and a high reflect standard on both ports (ports 1 and 2).
3) Uncertainty due to cable flexing and connector repeatability was characterized by 20 repeat measurements of both a well-matched standard and a high reflect standard on both ports. The flexible RF cable was moved, and the standards were disconnected from the VNA and reconnected with a different orientation between measurements.
4) The power meter uncertainty was accounted for by uncertainty data provided by the manufacturer of the power meter.

To characterize large-signal amplifier parameters, the VNA was calibrated with an SOLR vector calibration and also with source and receiver power calibrations using a Keysight N1813A power meter and an N8485A power sensor. The uncertainties in the vector calibration and in the power meter were propagated by VNA-DUO to the power measured by the receivers at ports 1 and 2 of the VNA.

The source and receiver power calibrations were performed at a fixed source power of -5dBm. It is only necessary to connect the power sensor to port 1 of the VNA during calibration, since the power calibration is then transferred to the receivers on port 2 using the vector calibration. To capture non-linear parameters of amplifiers, the measurements were made by sweeping the source power level between -15 dBm and +5 dBm. Measurement results for a ZX60-83LN-S+ amplifier from Mini-Circuits Corp. are presented in this paper. Measurements were made over the frequency range between 0.5 GHz and 8 GHz.
A Keysight N705B power supply was used to apply DC bias to the amplifier and the voltage and current reading were taken directly from the power supply unit. The receiver powers together with the corresponding upper and lower uncertainty limits were displayed as traces on the VNA screen and all traces were saved as MDIF files.
The uncertainties in the measured amplifier parameters such as P_{IN}, G_{P} and $P_{1\mathrm{dB}}$ ($u(P_{\mathrm{IN}})$, $u(G_{\mathrm{P}})$ and $u(P_{1\mathrm{dB}})$) were calculated using (3), (4), and (6), respectively.

MEASURED RESULTS

Small-signal parameter results

The uncertainty enabled SOLR calibration of the PNA-X was carried out between 0.5 GHz and 8 GHz. The S-parameters of the ZX60-83LN-S+ amplifier were measured and the measurement uncertainties were evaluated. The amplifier was biased with a DC voltage of +5V and a DC current of 60 mA. The measured small-signal gain (S_{21}) and reflection coefficients (S_{11} and S_{22}) and their corresponding measurement uncertainties are plotted in Fig 2. The results show that the uncertainty in S_{21} is less than 0.045 dB. The uncertainty in S_{11} and S_{22} depends on the value of the reflection coefficient. For measured reflection coefficients up to -30 dB, the uncertainty is up to 1 dB.

Large-signal parameter results

Large-signal parameters of the amplifier were measured with the excitation applied to port 1 of the DUT and with the excitation source power set at levels from -15 dBm to +5 dBm. The incident and scattered wave amplitudes (A_1, A_2, B_1, and B_2) were measured together with their respective maximum and minimum uncertainty limits. From the measured wave results and associated uncertainties, the uncertainties in various amplifier parameters were determined using methods discussed in the section entitled “Evaluation of Uncertainties”. The amplifier’s measured output power (P_{out}) vs input power delivered (P_{in}) at 2, 5, and 8 GHz are plotted in Fig. 3. The results show that the amplifier gain starts to drop at an input power between -5 dBm and 0 dBm and that it is well compressed at an input power of +5 dBm for all frequencies. The power gain, G_{P}, of the amplifier measured between 0.5 and 8 GHz at different input powers is plotted in Fig. 4. (a) The results show that the amplifier gain is compressed by more than 3 dB at P_{in} of +5 dBm confirming that the amplifier is operating in its non-linear mode of operation for this value of input power. The measured $P_{1\mathrm{dB}}$ of the amplifier, along with the associated uncertainty, is plotted in Fig. 4. (b) The upper and lower uncertainty bounds are for a confidence level of 95%.

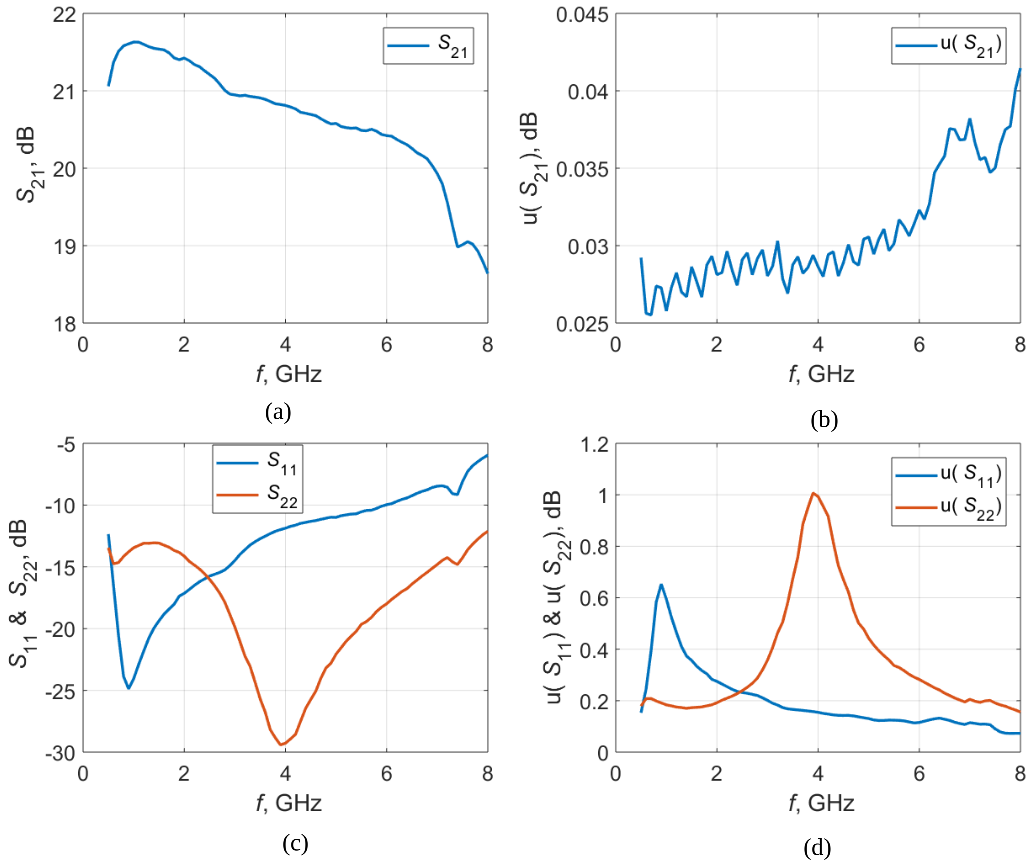


Fig. 2. Measured small-signal performance of ZX60-83LN-S+ amplifier (a) small signal-gain (S_{21}), (b) uncertainty in small-signal gain (S_{21}), (c) S_{11} and S_{22}, and (d) uncertainty in S_{11} and S_{22}.

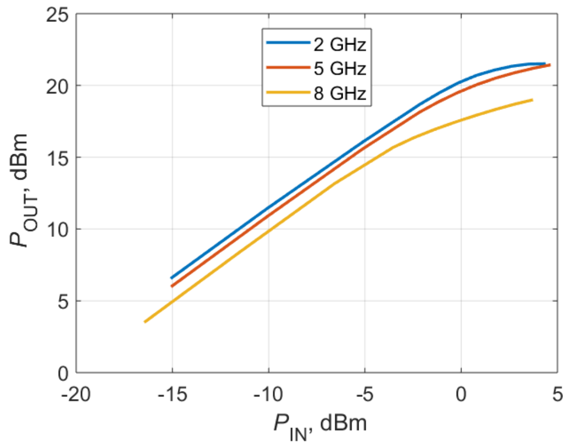
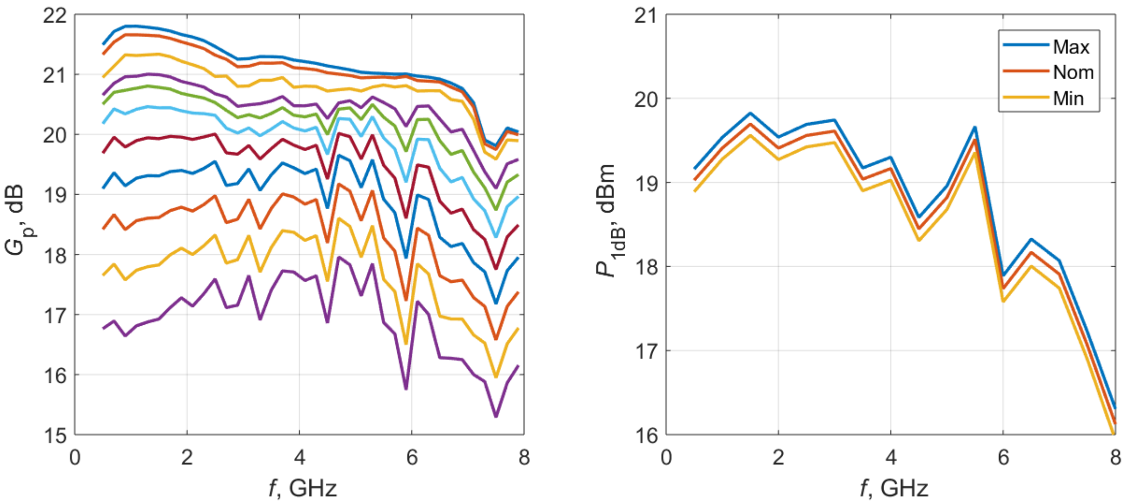


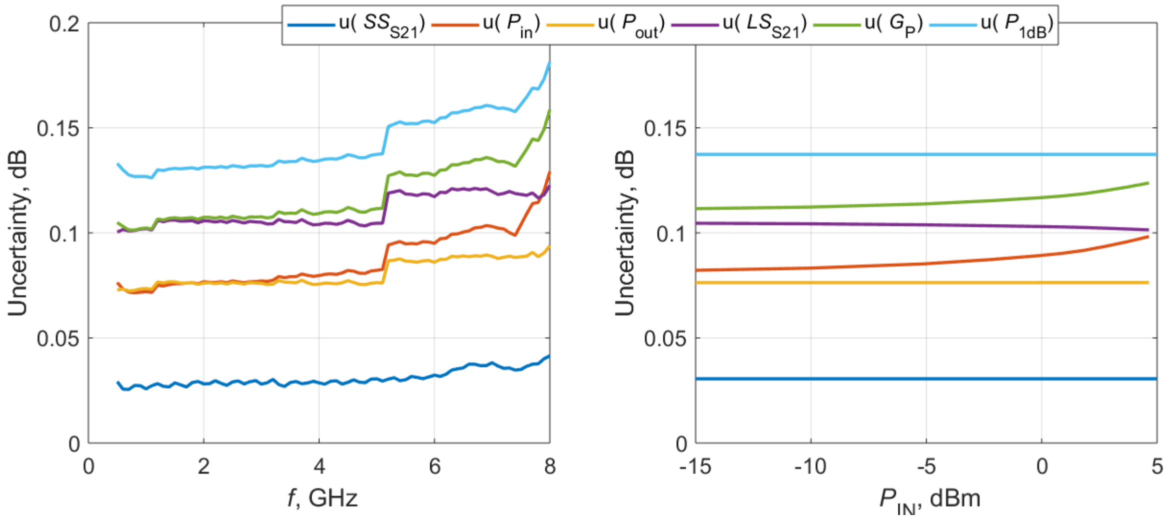
Fig. 3. Measured P_{OUT} versus P_{IN} of the amplifier.



(a) (b)

Fig. 4. The measured power gain and compression of the amplifier. (a) G_{P} at different P_{in} (-15 dBm (blue) to +5 dBm (purple) in 2 dB steps), and (b) $P_{1\mathrm{dB}}$ of the amplifier with minimum and maximum uncertainty limits.

The uncertainty in P_{IN}, $u(P_{\mathrm{IN}})$, was calculated using equation (3) and the uncertainty in $P_{\mathrm{OUT}} = |B_2|^2$, $u(P_{\mathrm{OUT}})$, depends only on the uncertainty in B_2 because the amplifier was measured into a 50 Ω matched load. The uncertainty in G_{P}, $u(G_{\mathrm{P}})$, was calculated using equation (4) and the uncertainty in the $P_{1\mathrm{dB}}$, $u(P_{1\mathrm{dB}})$, was calculated using equation (6) from the measured data. The measurement uncertainties in these large-signal parameters of the amplifier are plotted in Fig. 5. The plot also includes uncertainties in small-signal gain, $u(SS_{\mathrm{S21}})$, from Fig. 2(b) and uncertainties in large-signal gain, $u(LS_{\mathrm{S21}})$, where $LS_{\mathrm{S21}} = B_2/A_1$.
The results show that for the power dependent amplifier measurements, $u(P_{\mathrm{out}})$ is between 0.07 and 0.09 dB. $u(P_{\mathrm{in}})$ is dependent on the input return loss of the amplifier as well as the uncertainties in the available power from the source. This results in slightly higher $u(P_{\mathrm{in}})$ at frequencies for which the input return loss of the DUT is higher.
The measurement uncertainty in LS_{S21} (measured with both a vector calibration and a power calibration) is between 0.1 and 0.12 dB whereas the uncertainty in SS_{S21} (measured with only a vector calibration) was only 0.025 to 0.045 dB. The main reason for the higher uncertainty in LS_{S21} compared to SS_{S21} is due to the uncertainty contribution from the power meter.
The measurement uncertainty in G_{P} is between 0.1 and 0.16 dB. The uncertainty in $P_{1\mathrm{dB}}$ is between 0.12 and 0.18 dB and $u(P_{1\mathrm{dB}})$ is around 0.03 dB larger than $u(G_{\mathrm{P}})$ and about 0.06 dB larger than $u(P_{\mathrm{IN}})$. It should be noted that the step in uncertainty at 5 GHz is mainly due to a change if the value of uncertainty in the power meter, as specified by the manufacturer.
Fig. 5(b) shows the measurement uncertainty in the analysed amplifier parameters plotted against P_{IN} at 5 GHz.



(a) (b)

Fig. 5. Measurement uncertainties for different large-signal parameters of the amplifier. (a) uncertainty plotted against frequency, and (b) uncertainty plotted against P_{IN} at 5 GHz.

DISCUSSION OF RESULTS

In our experiment, the uncertainties in the amplifier's small-signal parameters, which were characterized using S-parameters, are due to the calibration standards, electrical noise, cable flexing and connector repeatability. The measurement results show typical uncertainties that can be expected from such measurements.

The large-signal parameters include an additional source of uncertainty from the power meter. The uncertainties from these contributors have been propagated to the different amplifier parameters characterised using a VNA. The following results were obtained from our measurements:

a) The uncertainty in return loss depends on the magnitude of the reflection and can be accurately characterized using S-parameters.
b) The uncertainty in small-signal gain (S_{21}) is around 0.03 dB.
c) The uncertainty in large-signal gain is around 0.11 dB, i.e. around 0.08 dB larger than the small-signal gain. This shows that the uncertainty due to the power meter is the dominant source of uncertainty in large-signal measurements. The uncertainty in different types of amplifier gain can be determined. For example, in our analysis, small-signal, large-signal, and power gains were considered.
d) The uncertainty in input power depends on the input reflection coefficient of the amplifier as is evident in the increase in the uncertainties above 3 GHz.
e) The uncertainty in power gain is around 0.03 dB larger than the uncertainty in the input power.
f) The uncertainty in the 1 dB gain compression point is around 0.03 dB larger than the uncertainty in the power gain.

The power meter uncertainty is a dominant factor in the measurement uncertainty for large-signal parameters. The manufacturer-supplied power meter uncertainty information was used in our experiment. It is also possible to independently characterize the power meter uncertainty and provide this uncertainty information in VNA-DUO.

SUMMARY AND CONCLUSIONS

Methods to quantify the measurement uncertainties associated with some basic parameters characterizing the linear and non-linear operation of an amplifier have been presented in this paper. These methods have been applied to measurements of several amplifiers and results have been presented here for one of these amplifiers. A similar methodology could be deployed to analyze other amplifier parameters.

A VNA can be used to characterize parameters such as return losses, small-signal gain, input power, output power, large-signal gain, 1 dB compression point, etc, which describe the small-signal and large-signal behavior of an amplifier. To characterize the large-signal parameters, an extra step involving a power meter is required in the calibration of the VNA. This paper has shown that VNA-DUO can be used to provide an estimate of the uncertainty in these amplifier parameters. The uncertainty in the large-signal parameters were found to be larger than the uncertainty in the small-signal parameters and this is mainly due to the uncertainty in the power meter used to calibrate the VNA for large-signal measurements.

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