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Effects of nonlinearities from the analog frequency-ramps of the fast network-analyser

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Abstract. The developed network analyser with four ports allows very fast measurements of S-parameters in comparison with a conventional network analyser. This is possible because highly linear analogue frequency ramps are used. Thus the settling times of stepped frequency sweeps of conventional analysers are eliminated. The required high linearity and high stability of the frequency ramps is achieved by using fractional divider phase locked loop circuits.

For a practical realization it is necessary to accept small nonlinearities for the linear analogue frequency ramps. For this reason investigations were performed to clarify effects of small nonlinearities on the measurement precision.

Nonlinearities are willingly implemented by programming the fractional frequency ramps accordingly. The gained expertise allows for a further improvement of measurement accuracy and dynamic range.

1 Introduction

In the area of metrology it is often important to measure complex-valued scattering parameters very fast. Examples are the high volume production in the industry, applications like impulse measurements or systems, which are in motion. Such a fast four port network analyser may be based on highly linear analogue frequency ramps. By the use of these ramps the settling time for discrete frequency steps is practically eliminated. The requirements of linearity and stability for these frequency ramps are very high. In order to obtain a cost effective industrial implementation of the system, some small nonlinearities must be tolerable. The following investigation will demonstrate the behaviour of a system with small nonlinearities, in particular the measurement accuracy and the dynamic range.

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2 Network analyser structures

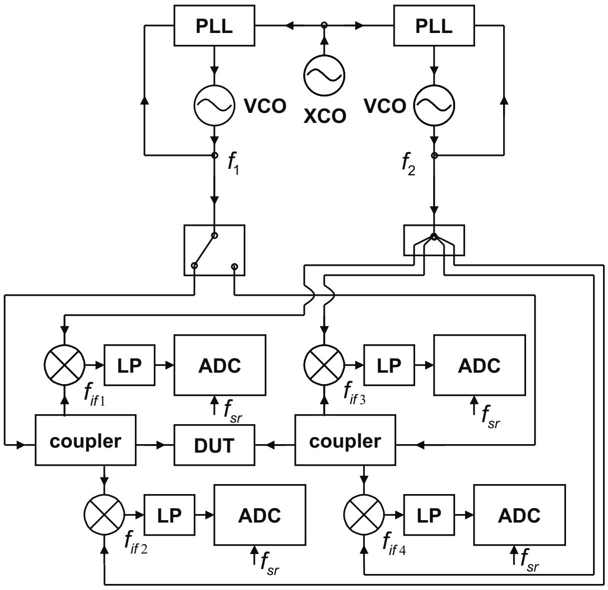
The fast network analyser shows a structure similar to a conventional four port network analyser. A block diagram of the system used is shown in Fig. 1.

The microwave signals are generated by the two linear frequency ramp systems, which both consist of one VCO and one fractional phase locked loop circuit. Both systems are linked via a synchronization line and are driven by a reference oscillator of 12.5 MHz. The VCOs are swept over a frequency range from 4 GHz to 5.5 GHz in 20 ms with a fixed frequency difference of 48 kHz. One of these signals is used as the measurement signal while the other one is used as the L.O.-signal. The first one is led through a switch, through the couplers and then to the device under test. From there the signal passes on to the four mixers and is down-converted with the L.O.-signal to the low intermediate frequency which is digitised. The recorded data are transferred to the PC and then evaluated. For the fast network analyser the reproducibility of samples is of particular importance. Therefore the four analog digital converters are driven by the same reference oscillator as the phase locked loop circuits.

The total measuring time of one object under test (DUT) takes 40 ms, because each measurement consists of two switch settings with 10 ms for one frequency ramp. Thus this system is approximately 20 times faster than a conventional network analyser.

The whole structure of the fast network analyser is similar to the structure of a conventional network analyser. In particular all known calibration techniques and also self-calibration techniques can be used for this network analyser, and therefore new calibration algorithms need not to be developed.

An important difference between the fast and the conventional network analyser exists concerning the data processing. For the fast network analyser a complete record of the frequency sweep is needed for the evaluation in contrast to the conventional one, which uses frequencies point by point.



VCO = 4 GHz to 5,5 GHz

XCO = 12.5 MHz

f_{sr} = 1,25 MHz: sampling rate

f_{if_i} = 48 kHz: i = 1..4, intermediate frequency

ramp bandwidth ΔF = 1,5 GHz

ramp duration: T_m = 20 ms

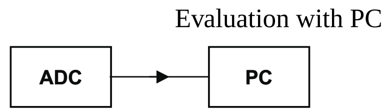


Fig. 1. block diagram of the fast network analyser.

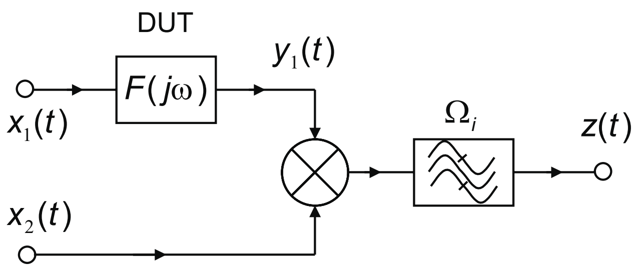


Fig. 2. model of a measuring port.

Thus a special technique is used to evaluate the data. This special evaluation procedure is described in the next section.

3 A special analysis technique

To explain this special analysis technique a measuring port is represented as a mathematical model, which is shown in Fig. 2.

For a continuous sampling the signals x_1 and x_2 can be defined as

$$x_1(t) = \mathrm{Re}\{\mathrm{e}^{j\Phi_1(t)}\} \tag{1}$$
$$x_2(t) = \mathrm{Re}\{\mathrm{e}^{j\Phi_2(t)}\}. \tag{2}$$

The phases in these equations are

$$\Phi_1(t) = \Omega_0 t + \pi\sigma t^2 \tag{3}$$
$$\Phi_2(t) = (\Omega_0 - \Omega_i)t + \pi\sigma t^2. \tag{4}$$

The ramp steepness σ is defined as the ratio of bandwidth to rise time:

$$\sigma = \frac{\Delta F}{T_m}. \tag{5}$$

In order to obtain the frequency response of the DUT, the signal $z(t)$ is required:

$$z(t) = \frac{1}{2}\mathrm{Re}\{F(j\Omega(t))\mathrm{e}^{j\Phi_i(t)}\}. \tag{6}$$

This can be accomplished via the analytical signal with two Fourier transformations. Thus the following expression holds:

$$z_+(t) = \frac{1}{2}F(j\Omega(t))\mathrm{e}^{j\Phi_i(t)}. \tag{7}$$

This is a simple way to obtain the frequency response modified with an exponential function $\mathrm{e}^{j\Phi_i(t)}$. This exponential function can be eliminated by constructing ratios because it is the same for all analytical signals. To calculate S-parameters, ratios must be taken between different analytical signals as well. As an example for the transmission a ratio between the wave, which is incident to the DUT, and the wave which is transmitted through the DUT is the transmission coefficient S_{21}. The S-parameters can be specified very fast with this evaluation method.

4 Different i.f.-signals

For the measurement comparison different types of frequency ramps are used. One approach is based on two high precision frequency ramps (ramp type A). For this system both frequency ramps have a linearity error of less than

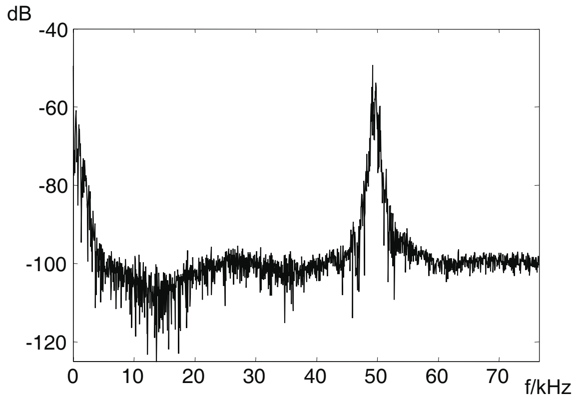


Fig. 3. i.f.-signal with a high precision frequency ramp, ramp type A.

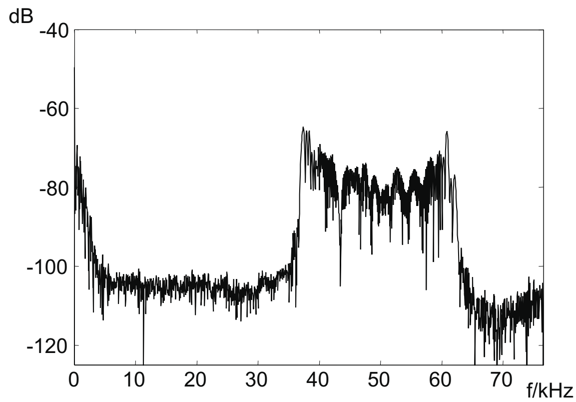


Fig. 4. i.f.-signal with a low precision frequency ramp, ramp type B.

25 Hz. Thus the relative linearity error is $\frac{\Delta F_{max}}{\Delta F} \leq 1.6 \cdot 10^{-8}$. This high linearity is reflected in Fig. 3. The figure shows an i.f.-signal of this system, which is a very narrow band signal. Thus it is suitable for the evaluation, because the necessary bandpass filter can be kept narrow. To simulate linearity errors of the frequency ramps, for one of the ramps a sinusoidal frequency modulation is added to the linear sweep. The deviation of this sweep to the linear one is at the maximum 12.5 kHz (ramp type B). Thus the relative linearity error is $\frac{\Delta F_{max}}{\Delta F} \leq 8.3 \cdot 10^{-6}$. The corresponding i.f.-signal is shown in Fig. 4. This signal is not as narrow band as the one before, because the signal has a bandwidth of approximately 25 kHz. This fact must be considered in the evaluation. The i.f. bandpass filter must be correspondingly larger.

5 Measurements

To examine the effects of nonlinearities of the frequency ramps, one measurement is performed with two high precision ramps (ramp type A) while another one uses one high (ramp type A) and one low precision ramp (ramp typ B) for comparison. A bandpass filter at 5 GHz is used as the device under test, because it is a suitable measurement object to test

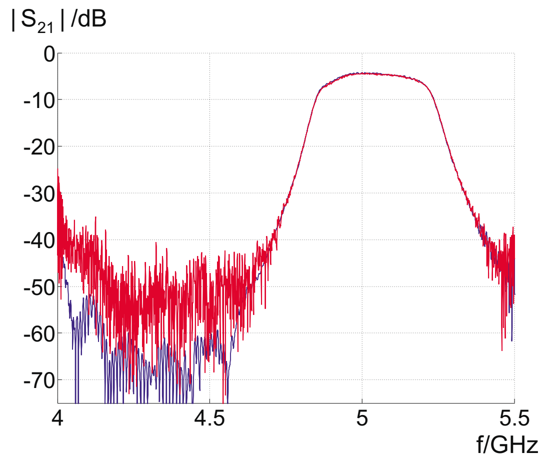


Fig. 5. Magnitude of S_{21} of 5 GHz bandpass filter. Red lines: frequency ramp with linearity error, blue lines: frequency ramp without linearity error.

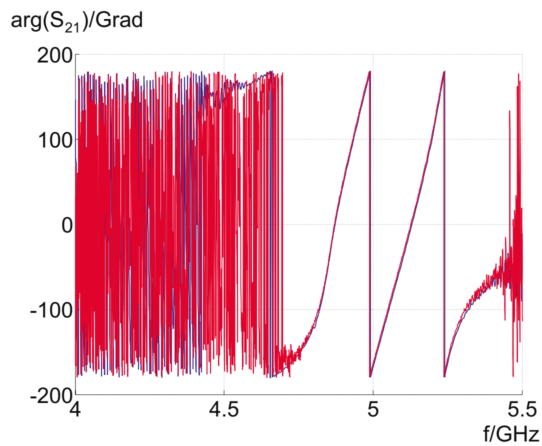


Fig. 6. Phase of S_{21} of 5 GHz bandpass filter. Red lines: frequency ramp with linearity error, blue lines: frequency ramp without linearity error.

the dynamic range. This bandpass is realized in microstrip technique. All measurements are fully calibrated. The applied calibration method is a TRL-calibration with coaxial standards. For the measurements with the low precision frequency ramp (ramp type B) there are two different ways of using this ramp. For one case the same ramp type B is used for each measurement. This means that every measurement i.e. either the calibration or the device under test is executed with this ramp. In the other case the ramp type B is only used for the measurement of one setting of the switch, while for the other setting of the switch the ramp type A is used.

The magnitude and the phase of S_{21} of the bandpass filter are displayed in Figs. 5 and 6. Both figures show that the fast network analyser works with the low precision frequency ramp (ramp type B) nearly as well as with two high precision ramps (ramp type A). The accuracy is identical in both types of measurement. This is shown in Figs. 5 and 6 for the magnitude as well as for the phase. The only major difference

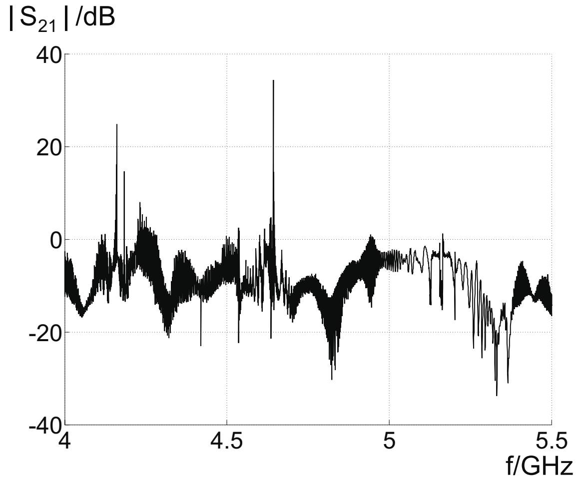


Fig. 7. Magnitude of S_{21} of 5 GHz bandpass filter with a frequency ramp with high linearity errors.

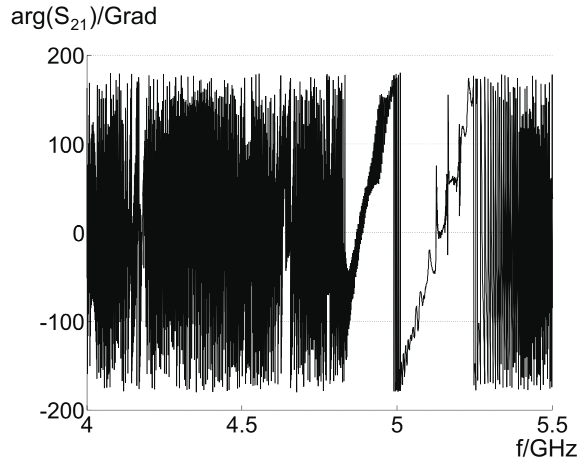


Fig. 8. Phase of S_{21} of 5GHz bandpass filter with a frequency ramp with high linearity errors.

appears in the dynamic range of the system. The system with two high precision ramps (ramp type A) has a 15 dB greater dynamic range. The reason for this is the smaller bandwidth of the i.f. bandpass filter employed for the evaluation of the signals.

Since there is no major difference between the two cases, i.e. ramp type A and ramp type B or only ramp type B, only one measurement is shown. This means, that it is not important if there is only one slightly nonlinear ramp or two. One nonlinear ramp already decreases the dynamic range of the whole system as much as two nonlinear ramps.

Another important fact is that the frequency sweep is not responsible for the loss of the dynamic range. If both frequency ramps show the same sinusoidal sweep, but with a constant frequency distance between them, then the i.f.-signal is again narrow band. Therefore only deviations of the constant i.f.-signal are responsible for the loss of dynamic range.

At least one system was examined with even larger linearity errors than for the cases that have been discussed so far. Indeed the variation of the sinusoidal sweep to the ideal linear sweep is 50 kHz at the maximum (ramp type C). Consequently the relative linearity error is $\frac{\Delta F_{max}}{\Delta F} \leq 3.3 \cdot 10^{-5}$. With this network analyser system it is impossible to make meaningful measurements. If the linearity errors are so large that the spectrum is folded into the image band, the system fails. This is shown in Figs. 7 and 8.

This becomes evident by observing the magnitude of S_{21} as well as the phase of S_{21} in both figures, showing that the network analyser does not work. The reason for this is that the i.f. signal is smaller than the frequency deviation and therefore the i.f. signal shifts into the image band. Thus the uniqueness for the evaluation is lost.

6 Conclusion

The effects of nonlinearities of the frequency ramps in the fast network analyser have been analyzed. This network analyser has the same structure as a conventional four port network analyser. All known calibration techniques can be used. The analysis technique is different to the conventional one, because the whole data record of a frequency sweep is evaluated concurrently and not frequency point by frequency point. For this reason it is necessary to determine the analytical signal to acquire the S-parameters.

A comparison of the system with two highly linear frequency ramps with a system with only one slightly nonlinear frequency ramp has shown that small nonlinearities predominantly produce a loss of dynamic. At a threshold value of the frequency nonlinearity, i.e. when the frequency linearity error becomes larger than the i.f. signal bandwidth, the fast network analyser completely fails to work.

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