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Noise Figure and S-Parameter Measurement Setups for On-Wafer Differential 60GHz Circuits

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Abstract — On-wafer measurement setups are introduced for measuring the noise figure and s-parameters of differential 60GHz circuits. The need for expensive four-port mm-wave vector network analyzers is circumvented by using magic-Ts, providing a minimum CMRR of 20dB, in combination with cheaper two-port mm-wave network analyzers. Waveguide interfaces are used in the vicinity of the RF probes to achieve a robust and repeatable setup, as the cables at mm-wave frequencies are prone to impedance and delay variation due to movement and bending. The noise figure of a double-balanced 60GHz mixer and the noise figure and s-parameters of a differential 60GHz LNA are measured using this setup and the measurement results are in good agreement with the simulations.

Index Terms — 60GHz, differential, measurement, mm-wave, noise figure, s-parameter.

I. INTRODUCTION

The number of applications envisioned for mm-wave frequencies has been rapidly growing during the recent years. Wireless high definition media interface (HDMI) at 60GHz, automotive radar at 77GHz, and imaging at 90GHz are just a glimpse of applications planned or already implemented in mm-wave regime. Similar to any other electronic product, the devices and circuits designed for mm-wave applications require a stage of measurement and verification.

The very short wave-length of the signals at these frequencies makes the measurements very sensitive to the effective length and bending of the interfaces. Especially to perform on-wafer measurements one must pay utmost attention to the rigidity of the interfaces connected to the probes to keep all the connection lengths and orientations constant during the whole period of the measurement and calibration. Also special care must be taken to preserve the position of the probes on the bondpads and impedance standard substrates, since the measurement accuracy can be very much dependent on the positioning and landing of the probes.

Another difficulty of the mm-wave measurements arises from the overwhelming cost of the equipments needed for instrumentation. For instance, s-parameter measurement of a differential two-port mm-wave circuit would require a very expensive four-port network analyzer.

In this paper, measurement setups are introduced which use waveguide interfaces to provide the required rigidity in the vicinity of the probes and utilize magic-T single-ended-to-differential converters to facilitate the measurement of differential circuits. The noise measurement of a 60GHz double-balanced zero-IF mixer [1] and the noise and s-parameter measurement of a differential 60GHz LNA [2], using the introduced setup, are explained in the following sections.

II. NOISE FIGURE MEASUREMENT OF A DOUBLE-BALANCED MIXER

The waveguide setup used for on-wafer measurement of the differential circuits is illustrated in Fig. 1. In the case of the mixer, four probes are needed. The probe on the top of the picture is an eye-pass probe used for biasing. The probe at the bottom of the picture is a Cascade GSGSG microprobe suitable for up to 50GHz measurements and used here at the IF output of the DUT mixer. The other two probes on the left and right side are Cascade infinity GSGSG probes suitable for mm-wave signals and used here at the RF and LO differential inputs of the mixer. The waveguide structures are mounted on metal plates which are screwed to the probe station, preventing all kinds of unintentional movements in the setup.

Fig. 1. The waveguide-based setup including two magic-Ts for measuring a double-balanced mixer

Fig. 2 shows the block diagram of the setup used for the noise figure measurement using Y-factor method [3]. Due to lack of a 60GHz signal generator in the laboratory, a network analyzer is used to produce the 60GHz LO signal. The 60GHz noise source is connected via an isolator (to ensure 50Ohm termination for the noise source) and a waveguide to the magic-T and then to the RF port of the mixer. The differential IF output of the mixer is converted to single-ended via a hybrid and then connected to the spectrum analyzer via a low-frequency amplifier which covers 30MHz-4GHz. The spectrum analyzer is set to Noise Figure mode with the DUT specified as a downconverter with a 60GHz LO. The IF frequency range is set to 30MHz-2GHz. The 60GHz noise source generates noise only in the range of 60GHz to 75GHz. Therefore, another noise source is needed for calibration of the output path and the spectrum analyzer. Fig. 3 shows the block diagram of the noise calibration setup. The low-frequency amplifier is essential for obtaining good calibration results by amplifying the noise. Since two different noise sources are used, the ENR (excess noise ratio) list of the two noise sources must be manually entered in the spectrum analyzer. Both noise sources are controlled by the spectrum analyzer. The effect of the low-frequency amplifier and the cable, connecting the IF balun to the low-frequency amplifier, is automatically taken into account during the measurement; because they are in the calibration setup. However, the impact of the IF balun and the RF interfaces at the input of the DUT must be manually calculated after the measurement.

Fig. 2. Noise figure measurement setup for the mixer

Fig. 3. Noise figure calibration setup for the mixer

The measured CMRR of the magic-T and its connected waveguides is at least 20dB. The loss of the combination of the magic-T, waveguide structure, and the infinity probe is measured via two methods for confirmation. The first method is illustrated in Fig. 4. Using a delta measurement and utilizing the network analyzer as a signal generator, the amplitude of the 60GHz signal is measured by the spectrum analyzer, as shown in Fig. 4(a). Since the available spectrum analyzer does not support 60GHz range, a preselected millimeter mixer is used to downconvert the 60GHz signal to the supported range of the spectrum analyzer. Keeping the source signal amplitude constant, the magic-T and the probes are introduced into the setup, as shown in Fig. 4(b). A through of an impedance standard substrate is used between the probes. The difference in the readings of the two steps gives the loss of the introduced interface. Assuming a negligible loss for the through and equal loss for the two probes and magic-Ts, the loss of the RF interface, used between the noise source and the mixer input, can be calculated by dividing this number by two.

Fig. 4. Using delta measurement to measure the loss of the interface between the noise source and the mixer input: a) measuring without the RF interface under test, b) measuring with the RF interface under test

In the second method, two one-port calibrations are performed using the network analyzer. First a cable, used in the next step for connecting the network analyzer to the magic-T and probe, is calibrated and the calibration dataset is saved. Then an on-wafer one-port calibration is performed using an impedance standard substrate and including the magic-T and the probe in the setup. Again the calibration dataset is saved. Having the two datasets, the s-parameters of the magic-T and probe combination is calculated. The measured loss is the same as the one obtained from the first method (delta measurement).

To calculate the impact of the IF balun, the magic-T and waveguides, and the infinity probe, one has to take the measurement environment temperature into calculation. After calculations the final noise measurement results are obtained as shown in Fig. 5 which are close to the simulations.

Fig. 5. Measured and simulated noise figure of the mixer

III. NOISE FIGURE MEASUREMENT OF A DIFFERENTIAL LNA

The noise figure measurement of the 60GHz LNA is impeded by the fact that the output of the LNA is at a higher frequency than supported by the spectrum analyzer. Even the preselected mixer of Section II cannot be used here because the Noise Figure mode of the spectrum analyzer does not support it and it cannot be used with an external LO either. Therefore a passive mm-wave mixer is used in the noise measurement setup, as shown in Fig. 6, to downconvert the output of the LNA to the range of the spectrum analyzer. The passive mixer can be included in the calibration setup as shown in Fig. 7, obviating the need for its inclusion in post-measurement calculations. As shown in Fig. 8, the measured noise figure is in close agreement with the simulated values.

Fig. 6. LNA noise figure measurement setup

Fig. 7. Noise figure calibration for the LNA

IV. S-PARAMETER MEASUREMENT

Performing s-parameter measurements on differential circuits with a two-port network analyzer is also facilitated by utilizing the magic-Ts. As shown in Fig. 9, each port of the network analyzer is connected to a magic-T and then to the probes. SOLT (Short-Open-Load-Through) calibrations are performed on a standard impedance substrate, suitable for GSGSG probes. Then the impedance standard substrate is replaced by the DUT and the measurement is done. The measured transducer gain of the 60GHz LNA, using this setup, is compared with simulation results in Fig. 8.

To measure the common mode response the magic-Ts are connected in such a way that they provide common mode (CM) signals at input and output. The measured CM S_{21} , representing the CM transducer gain, after calibration is shown in Fig. 10, approximately equal to -2 dB, resulting in a common mode rejection of approximately 12

dB which is again in close agreement with the simulated value.

Fig. 8. Measured and simulated noise figure and transducer gain of the 60GHz LNA

Fig. 9. S-parameter measurement and calibration setup of a differential two-port circuit

Fig. 10. Measured common-mode S_{21} of the LNA

Conforming to the following considerations can promote the accuracy of the measurements and calibrations:

1. Accurate definition of the impedance standard substrate in the network analyzer or the software which controls the network analyzer
2. Precise positioning of the probes on the bondpads or on the impedance standard substrate
3. Repeating the calibration after some period due to invalidity of the calibration results after a certain period
4. Using undamaged samples of impedance standard substrate

VII. CONCLUSION

Using a waveguide-based measurement setup, accurate and repeatable measurements are performed on 60GHz receiver components. The fixed waveguide structures, specially provided for the probe station, serve for the robustness of the setup as they circumvent the need for cables, which are by nature difficult to rigidify, in the vicinity of the probes. Taking advantage of magic-Ts, it is possible to measure differential mm-wave circuits with a two-port network analyzer rather than using a much more expensive four-port one. Also the CM response of a differential circuit can be measured by reconfiguring the magic-Ts to provide CM excitation. The noise and s-parameter measurements performed on a 60GHz mixer and LNA yield consistent results with the simulations.

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