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Alexandre Boyer. A Low-Cost RF Detector to Enhance the Direct Power Injection Conducted Immunity Setup. *IEEE Letters on Electromagnetic Compatibility Practice and Applications*, 2022, 4 (4), pp.108 - 113. 10.1109/LEMCPA.2022.3210876 . hal-03794115

HAL Id: hal-03794115

<https://laas.hal.science/hal-03794115v1>

Submitted on 3 Oct 2022

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A Low-Cost RF Detector to Enhance the Direct Power Injection Conducted Immunity Setup

Alexandre Boyer

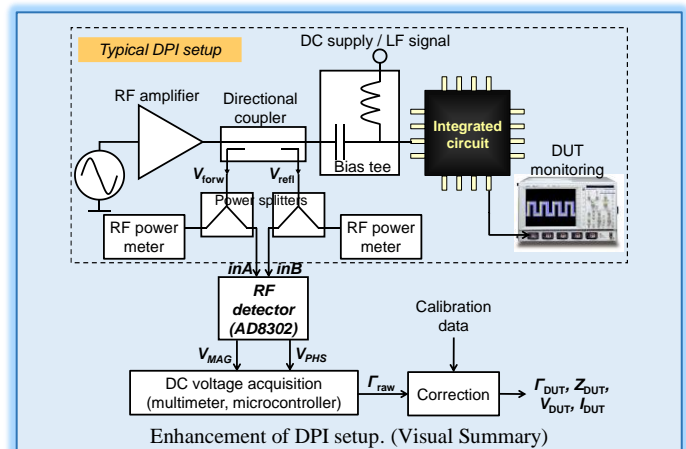
Abstract— Direct power injection (DPI) is a convenient method to characterize the conducted susceptibility of integrated circuits (IC). However, a practical issue of this test is that the voltage, current and impedance of the tested pin remain unknown during the test, even though it can provide valuable information to IC designers about IC failures. This letter presents an enhancement of the standard DPI test based on a commercial and affordable RF detector, which covers the frequency range of 5 MHz to 3 GHz. The proposed approach does not require specific measurement probes and board design constraints. It can be easily inserted in a conventional DPI test bench without any influence on the test results.

Index Terms—Conducted susceptibility test, Direct Power Injection (DPI), integrated circuit, RF detector

I. INTRODUCTION

Direct power injection (DPI) as defined by the standard IEC 62132-4 [1] is a commonly-used method to characterize the conducted susceptibility of integrated circuits (IC) over the range 150 kHz to 1 GHz [2]. The method consists of injecting a radiofrequency (RF) continuous wave disturbance to an IC pin in order to identify the amount of power required to induce a failure in a reproducible manner. The RF disturbance flows through a (bi)directional coupler and is capacitively-coupled to the IC pin through a bias tee. The susceptibility threshold is given as the power carried by the forward wave or forward power (P_{forw}) to generate an IC failure. In practice, it is measured by a power meter connected to the coupler terminals.

Numerous studies have been published to improve the DPI setup. In [3], the authors propose to improve the reproducibility of the test by a better control of the amplifier matching, common-mode current and a better bias tee design. Another common research topic is the extension of the frequency range, which is mainly related to the test board and bias tee design. In [4], authors propose board design guidelines to extend it up to 2 GHz. In [5], a bias tee is designed to extend the DPI test up to 8 GHz and up to 20 GHz for IC mounted in SOIC package in [6]. Another improvement direction is the extraction of the voltage and current at the IC input, which are more convenient electrical quantities for IC designers than P_{forw} as required by [1]. The simultaneous measurement of voltage and current also provides the impedance of the tested input-output (I/O). This information is also valuable for the designer to detect anomalous behavior during susceptibility test (e.g. unwanted triggering of an ESD clamp) or to build an equivalent electrical model of the tested I/O. [7] proposes a



method consisting of injecting the RF disturbance directly to the IC pin through a proprietary probe given between 40 MHz and 3 GHz [8], which embeds the coupling capacitor, a RF voltmeter and ammeter. However, the probe is costly and requires a specific ground plane adapter. An alternative solution called resistive RF injection probe (RFIP) was proposed in [9] and simplified in [10]. A shunt resistor is placed in series in the RF injection path to extract the voltage and current at the IC input after a de-embedding process. The method requires a wideband oscilloscope and two RF amplifiers to increase the sensitivity. The approach has been validated up to 1 GHz but, due to the current measurement uncertainties, the impedance extraction is degraded above 300 MHz.

In this paper, an enhancement of the DPI method is proposed to measure the electrical conditions (voltage, current and impedance) of the device under test (DUT) input pin. It is based on an affordable commercial gain and phase RF detector (AD8302 from Analog Devices), whose inputs are connected to the measurement terminals of

Take-Home Messages:

- The proposed method enables the extraction of electrical conditions of an IC pin (voltage, current, impedance) during a conventional DPI test.
- The method is based on a commercial and affordable gain and phase RF detector, and does not require intrusive and costly measurement probes and equipments.
- The method is valid from 5 MHz up to 3 GHz.
- Although it is based on the linearity assumption, it can provide an acceptable evaluation of voltage and current even in large disturbance regime.

the directional coupler. The proposed method is not intrusive and can be easily inserted to the typical DPI setup without any additional costly equipment. After a description of the principle of the method and the calibration process, a validation on two passive loads is presented. Then, the method is applied on two test ICs in order to extract the electrical conditions of the disturbed inputs during DPI.

II. PRINCIPLES OF THE PROPOSED DPI SETUP ENHANCEMENT

A. Principle of the Method

The purpose of the proposed DPI setup enhancement is to provide a convenient, non-invasive and affordable method to determine the electrical conditions of the tested IC pin during a DPI test (voltage, current, impedance). The most straightforward method to measure the voltage consists of placing an active high frequency voltage probe and using an oscilloscope. If the probe has a large enough bandwidth and small input capacitance, the measurement can be non-invasive and accurate up to several GHz, only if a carefully-designed footprint has been placed on the test board. The DUT impedance can be determined if the current is measured synchronously. The most straightforward approach consists of extracting it through a shunt resistor and differential voltage measurement in time-domain. In spite of the simplicity of the method at first sight, several practical issues may compromise the accuracy above several hundreds of MHz. The differential voltage measurement requires a careful design of the current probe, which has to be characterized properly up to several GHz. Moreover, to reach a sufficient sensitivity, either a large but intrusive resistance value should be placed, or some amplification should be provided with a good common-mode rejection.

In order to overcome these issues, an alternative method to extract voltage, current and impedance of the tested IC is based on the measurement of the forward and reflected waves, e.g. through a directional coupler as defined by the DPI standard. The DPI setup can be simplified to the equivalent electrical model presented in Fig. 1. The RF disturbance is produced by an equivalent RF voltage generator. The DUT is modeled by an impedance Z_{DUT} connected through the injection path, which is modeled by a Z_C -matched L -long transmission line. If the DUT is linear time-invariant, the analysis can be done in frequency domain. The voltage at any point x along the line is the superimposition of the forward and reflected waves, whose complex voltages are given by \widehat{V}^+ and \widehat{V}^- . They can be separated by a directional coupler. Here, we suppose that they are measured at the same point x_0 . The reflection coefficient $\widehat{\Gamma}_{DUT}$ at the DUT input is given by (1), where γ is the line propagation constant and $\widehat{\Gamma}_0$ the reflection coefficient seen from x_0 . (2) gives the DUT complex impedance \widehat{Z}_{DUT} from $\widehat{\Gamma}_{DUT}$. The magnitude of the voltage and current at DUT input can be obtained from $\widehat{\Gamma}_{DUT}$ and the magnitude of the forward wave V^+ , as given by (3) and (4).

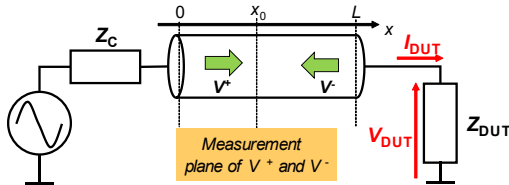


Fig. 1. Simplified equivalent model of the conducted injection setup in DPI

$$\widehat{\Gamma}_{DUT} = \frac{\widehat{V}^-(L)}{\widehat{V}^+(L)} = \frac{\widehat{V}^-(x_0)}{\widehat{V}^+(x_0)} e^{-2\gamma(L-x_0)} = \widehat{\Gamma}_0 e^{-2\gamma(L-x_0)} \quad (1)$$

$$\widehat{Z}_{DUT} = Z_C \frac{1+\widehat{\Gamma}_{DUT}}{1-\widehat{\Gamma}_{DUT}} \quad (2)$$

$$|\widehat{V}_{DUT}| = |\widehat{V}^+(L)| |1 + \widehat{\Gamma}_{DUT}| \quad (3)$$

$$|\widehat{I}_{DUT}| = |\widehat{V}^+(L)| |1 - \widehat{\Gamma}_{DUT}| \quad (4)$$

In a typical DPI setup, only the magnitude of V^+ and V^- are measured, so only the magnitude of $\widehat{\Gamma}_{DUT}$ can be extracted. Without the phase of $\widehat{\Gamma}_{DUT}$, neither \widehat{Z}_{DUT} , nor \widehat{V}_{DUT} , nor \widehat{I}_{DUT} can be determined. The proposed solution solves this issue by providing a simple method to measure the phase difference between \widehat{V}^+ and \widehat{V}^- .

B. Description of the Setup

In a conventional DPI setup, the measurement of forward and reflected power through a directional coupler and a power meter is not sufficient to determine V_{DUT} , I_{DUT} and Z_{DUT} , because the phase is not acquired. In order to avoid the use of a specific and costly measurement equipment, a commercial RF circuit (AD8302) has been identified [11]. This RF gain and phase fully-integrated detector is dedicated to the control of the gain and phase of receiving/transmitting applications up to 2.7 GHz. It delivers the gain and the phase between two RF signals connected to the inputs inA and inB in the form of two DC signals (called V_{MAG} and V_{PHS} respectively), as long as the input powers are comprised between -60 dBm and 0 dBm and their ratio between -30 and $+30$ dB. Connected to the terminals of a bidirectional coupler, the complex reflection coefficient can be extracted. The output voltage can be acquired by a dual input multimeter or the analog inputs of an acquisition board or a microcontroller. A resolution of some mV is enough to reach an acceptable measurement accuracy of $\widehat{\Gamma}_0$. The complete set-up is described in the visual summary (in page 1). The RF detector is added to the DPI test bench, without any changes in the RF injection path. The directional coupler HP772D is used in the presented results. Its coupling factor is nearly constant and equal to -20 dB above 1 MHz, but it decreases linearly below 100 MHz. This effect degrades the sensitivity of the DPI test results and the extraction of V_{DUT} , I_{DUT} and Z_{DUT} , especially below 1 MHz. The forward and reflected power magnitudes are still measured by a power meter. Both inputs inA and inB are connected to the coupler terminals through two RF power splitter (ZFRSC-42-S+ from Mini-Circuits). To ensure the best accuracy, V_{MAG} and V_{PHS} are sensed by two digital multimeters (Agilent 34405A). The AD8302 evaluation board (AD8302-EVALZ) is directly used for the validation tests [12]. Fig. 2 shows its configuration during the DPI test.

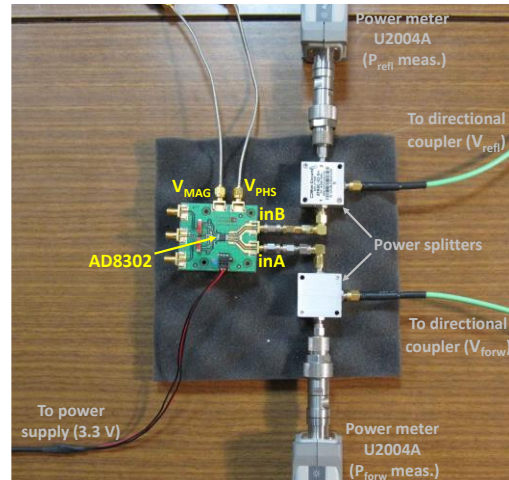


Fig. 2. Configuration of the RF detector board

C. RF Detector Calibration

Although the gain sensitivity of the RF detector is stable according to the supply voltage and the temperature, it varies according to the frequency and the input power, contrary to the phase sensitivity. Both gain and phase detections need to be calibrated in order to retrieve the actual gain and phase of $\hat{\Gamma}_0$ from the acquisitions of V_{MAG} and V_{PHS} by interpolation.

The gain and phase calibration setups are illustrated in Fig. 3. The gain calibration consists of measuring the evolution of V_{MAG} according to the ratio between the power applied on inA and inB, at different frequency and power applied on inA. The signal produced by a RF generator is transmitted to both inputs through a power splitter. A variable attenuator is placed before inB to control the ratio between the power applied on inA and inB. Fixed attenuators can also be inserted to protect both inputs from excessive power. The voltage V_{MAG} is measured with the same multimeter used in the DPI setup. The phase calibration consists of measuring the evolution of V_{PHS} according to the phase difference between two synchronized sine waveforms with identical frequency. Both signals are produced by a dual output signal generator (Tektronix AFG3102) in order to minimize the jitter between both signals. The amplitude of both signals can also be controlled to characterize the influence of the input signal powers on V_{PHS} .

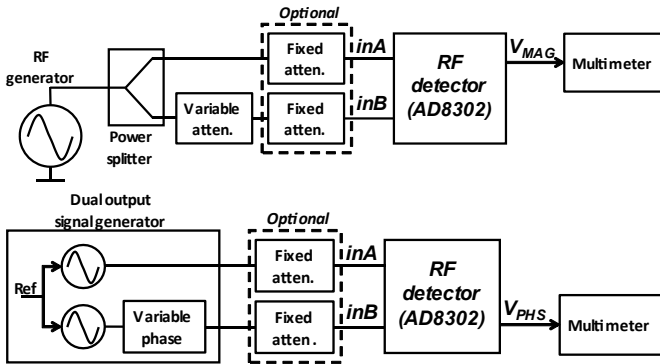


Fig. 3. RF detection calibration setup: gain (top) and phase calibration (bottom)

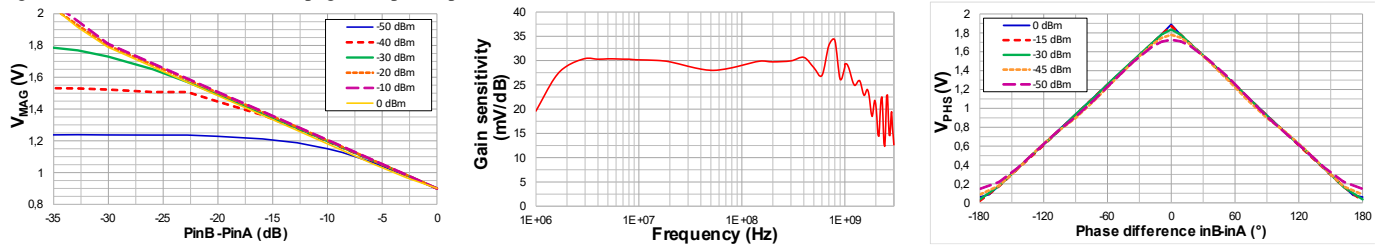


Fig. 4. Calibration of the RF detector: measurement of the evolution of V_{MAG} vs. the power ratio between inB and inA (left) and evolution of the gain sensitivity vs. frequency for $PinB = PinA$ (middle). Measurement of the evolution of V_{PHS} vs. the phase difference between the inputs for different input power (right)

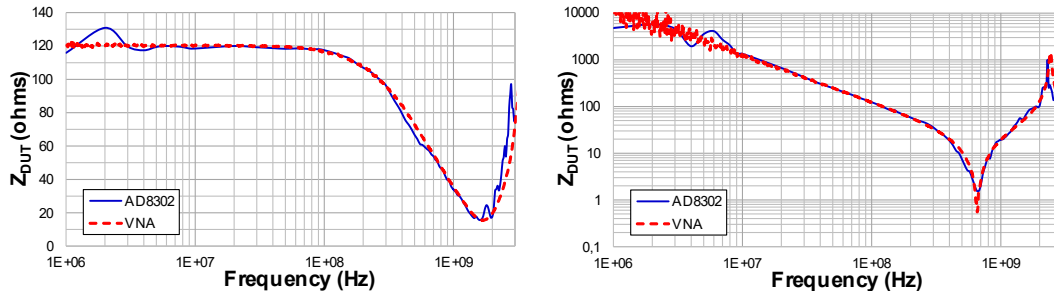


Fig. 5. Comparison between load impedance measured with VNA and extracted from AD8302: 120 Ω load (left) and 12 pF COG capacitor (right)

Fig. 4 (left and middle) shows the measured evolution of V_{MAG} according to the ratio between the power applied on inB and inA, which gives directly $|\Gamma_0|$, for different input power and the frequency. The gain sensitivity is nearly constant between 3 MHz and 1 GHz. The oscillation above 1 GHz may be due to the degradation of AD8302 input matching.

Fig. 4-right shows the evolution of V_{PHS} according to the phase difference between inB and inA and the input power, when the same power is applied on both inputs. The evolution is stable according to the frequency and the average phase sensitivity is about 10.5 mV/°. When the power decreases, the phase sensitivity tends to degrade around 0° and 180°. This result shows that the phase is only measured between 0° and 180°, which may create a phase ambiguity on the retrieved reflection coefficient. A simple algorithm has been developed to solve the phase ambiguity from the measured phase at different frequencies. The correction is based on two criteria. Firstly, the variation of the phase of $\hat{\Gamma}_0$ is mainly due to the phase difference introduced by the injection path (coupler, cables and bias tee), so that the phase of $\hat{\Gamma}_0$ decreases with frequency. If a positive evolution of the $\hat{\Gamma}_0$ is observed, the phase sign is corrected. Secondly, phase discontinuities closed to 0° and 180° are detected to decide if a sign change should be brought or not.

D. RF Injection Path Calibration

A preliminary calibration of the RF injection path is required to compensate the imperfections of the directional coupler (losses and directivity), the cables and power splitter (loss and delays) and the phase differences between the measured \hat{V}^+ and \hat{V}^- . Moreover, the calibration aims to move the calibration plane from the coupler output to the injection path output, which is considered to be the DUT input. This calibration step is based on the S-parameter characterization of each element of the injection patch by a vector network analyzer (VNA).

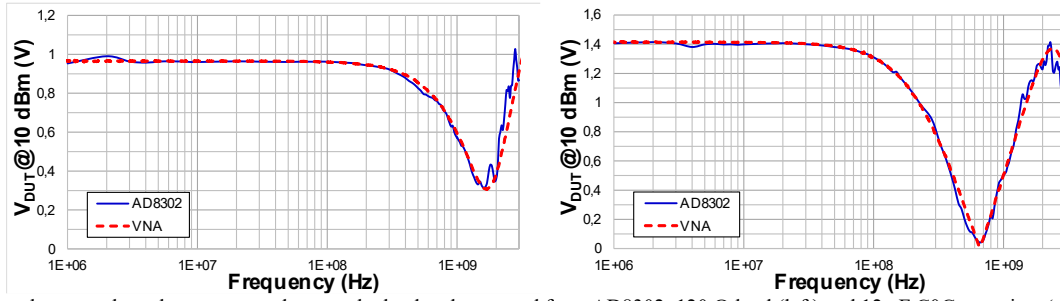


Fig. 6. Comparison between the voltage measured across the load and extracted from AD8302: 120 Ω load (left) and 12 pF COG capacitor (right)

III. VALIDATION ON PASSIVE LINEAR LOADS

A first validation test of the proposed DPI setup enhancement consists of extracting the impedance and the voltage of two passive linear loads: a 120 Ω thin-film resistor and a 12 pF COG capacitor. They terminate a short microstrip line, directly connected through a SMA connector to the directional coupler output (100 MHz to 2 GHz). P_{forw} is set to 10 dBm over all the frequency range (1 MHz to 3 GHz). The impedance extracted by the RF detector is compared to a reference measurement provided by a VNA (Rohde & Schwarz ZVL, 9 kHz to 6 GHz). The VNA and the coaxial cables used to connect the DUT are calibrated according to a short-open-load-through calibration procedure. The voltage across the loads are deduced from the measured P_{forw} and the impedance acquired by the VNA. The comparisons of the measured load impedance and voltage are presented in Figs. 5 and 6. The current is not presented as the tested loads are passive and linear. A good agreement between the impedances and the voltages extracted by the RF detector and the VNA can be observed between 10 MHz and 2 GHz. Local differences can be explained by the calibration uncertainties. The degradation below 5 MHz is due to two factors: the reduction of the gain sensitivity of the RF detector below 3 MHz, and the low coupling factor of the directional coupler which limits the power applied on inA and inB in the MHz range. Above 2 GHz, a frequency shift between both measurement results appears. It is certainly due to the calibration

differences, so that the calibration planes do not coincide exactly. In spite of fluctuations of the measured impedance and voltage, the trends and the orders are correctly determined up to 3 GHz.

IV. CHARACTERIZATION OF THE SUSCEPTIBILITY OF ICs

In this section, the RF detector is used to extract the electrical conditions at an IC input pin during an actual DPI test. Two case studies are proposed, which differ according to the linear operation of the tested structures under RF disturbance injection.

A. Case study 1: analog input of a bandgap reference

The DPI test is performed on the power supply input of a bandgap voltage reference (LT1798 from Linear Technology), which delivers a constant 2.5 V voltage from a 5 V power supply voltage. A 100 nF decoupling capacitor is mounted close to the IC input, as recommended by the manufacturer. The RF disturbance is superimposed to the power supply by a bias tee, given between 5 MHz and 3 GHz. Any RF disturbance coupled on the supply input generates a DC offset. During the DPI test, the output voltage is monitored by an oscilloscope and a failure is detected if the DC offset exceeds ± 20 mV. The maximum P_{forw} is set to 33 dBm. The RF voltage and current applied at the IC input are also measured with an oscilloscope and a pick-off tee (HPPI PT45A) or a current sensor (HPPI CS-0V5-A), given up to 3 GHz. The bias tee, the pick-off tee and the current sensors are considered during the calibration of the RF injection path. The input impedance of the unbiased IC is also measured with a VNA.

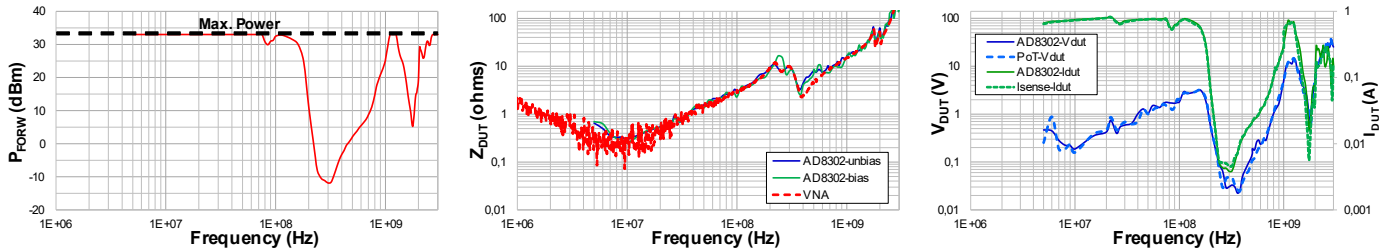


Fig. 7. Measured susceptibility threshold of the LT1798 voltage reference (left). Comparison of the input impedance measured with VNA and extracted from AD8302 (middle). Comparison of the voltage and current measured at the IC input at P_{fail} (right)

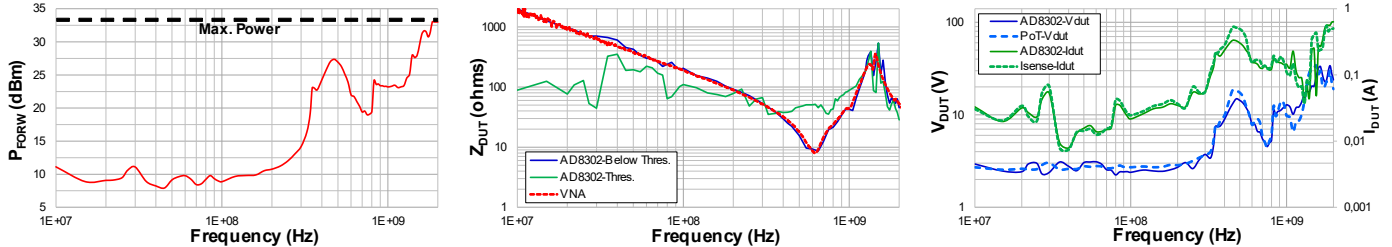


Fig. 8. Measured susceptibility threshold of the MCU input (left). Comparison of the input impedance measured with VNA and extracted from AD8302 (middle). Comparison of the voltage and current measured at the IC input at P_{fail} (right)

Fig. 7-left shows the susceptibility threshold (P_{fail}) the IC. No failure is detected below 75 MHz due to the action of the decoupling capacitor. The IC is particularly susceptible around 300 MHz and 1.75 GHz. During the DPI test, the IC input impedance is extracted by the RF detector at the failure level. The same measurement is also done when the IC is unbiased and a constant P_{forw} (10 dBm) and compared with VNA measurement, as shown in Fig. 7-middle. The three curves are similar, proving the IC behaves linearly, even in the presence of a RF disturbance. The voltage and current at the IC input at P_{fail} are also extracted with the RF detector, and compared with the direct measurement as shown in Fig. 7-right. A good agreement is observed, except below 10 MHz and close to the immunity minima because of the reduced amount of power applied on the AD8302 inputs.

B. Case study 2: digital input of a microcontroller

The DPI test is done on a digital input of the 32-bit microcontroller (MCU) STM32F030R8 using the same injection path and test conditions than in the previous case study. During the DPI test, the input is pulled down and its logical state of the tested input is regularly sensed. Moreover, the operation integrity of the MCU is also checked. A failure is detected if the logical state of the input is modified or if the MCU operation is affected by the RF disturbance. The RF voltage and current applied at the IC input are also measured.

Fig. 8-left shows the susceptibility threshold of MCU input. Up to 325 MHz, the failure is related to a change of the logical state of the tested input. Above this frequency, the disturbance leads to an interrupt of the MCU, whose recovery requires a manual reset. No failures are detected above 1.8 GHz. During the DPI test, the input impedance is extracted from the RF detector measurement, at P_{fail} and 20 dB below P_{fail} . These measurements are compared with the VNA measurement made at -10 dBm (Fig. 8-middle). The impedance extracted by the RF detector below P_{fail} is in good agreement than the VNA result, and shows a capacitive behavior up to 600 MHz. However, the extracted impedance changes with P_{forw} and presents a completely different profile at P_{fail} . This result reveals that the input behaves non-linearly close to P_{fail} . An oscilloscope measurement of the RF voltage at the MCU input confirms this distortion due to the triggering of the on-chip ESD clamps. This phenomenon can be deduced from the impedance extracted by the RF detector, which presents a significant resistive behavior related to the ESD protection clamping.

Although the linearity assumption is not met, V_{DUT} and I_{DUT} are computed at P_{fail} from RF detector results and compared with direct measurements. As shown in Fig. 8-right, the RF detector provides an acceptable evaluation of the peak-to-peak amplitude of V_{DUT} and I_{DUT} up to 2 GHz. A gap appears around 500 MHz, which is related to a severe distortion of the RF disturbance. In spite of this loss of accuracy, the proposed method can provide an estimation of the electrical conditions of the tested IC pin, even in large disturbance regime.

V. CONCLUSION

This letter presents an enhancement of the standard DPI test based on a commercial gain and phase RF detector, to get access to the impedance, voltage and current of an IC pin during RF disturbance injection. These electrical quantities are much more beneficial for an in-depth analysis of IC susceptibility than the forward power as specified by the DPI test. Contrary to other existing methods, the proposed approach does not require any specific probes or board design constraints. It can be easily mounted on a conventional DPI test

bench without any impact on the susceptibility test results. The method has been validated from 5 MHz up to 3 GHz, due to operating range of the RF detector. Although the approach is based on the linearity assumption, the experimental results show that it can provide a reasonable estimation of the amplitude of voltage and current at the IC pin, even in large disturbance regime and ESD protection triggering. A possible perspective for this method is the extraction of a simple equivalent model of IC input for susceptibility prediction at board level, given in the form of an equivalent impedance and a failure level in voltage or current.

REFERENCES

- [1] IEC62132-4, Integrated circuits – Measurement of electromagnetic immunity – Part 9: Measurement of electromagnetic immunity 150 kHz to 1 GHz - Part 4: Direct RF power injection method, International Electrotechnical Commission, 2014.
- [2] Boyer A, Sicard E (2017), Basis of electromagnetic compatibility of integrated circuits, Presses Universitaires du Midi, 978-2-8107-0522-1.
- [3] Matsushima T, Ikehara N, Hisakado T, Wada O (2013), “Improvement of Reproducibility of DPI Method to Quantify RF Conducted Immunity of LDO Regulator,” in Proc. 9th Int. Workshop on EMC of ICs (EMC Compo), 2013, pp. 59-62, doi: 10.1109/EMCCompo.2013.6735173.
- [4] Pues H, Pissort D (2012), “Design of IEC 62132-4 Compliant DPI Test Boards that Work up to 2 GHz,” in Proc. Int. Symp. on EMC (EMC Europe 2012), 2012, doi: 10.1109/EMCEurope.2012.6396661.
- [5] Chang Y C, Hsu S S H, Peng K C, Chang Y T, Chen C K (2012), “The Practical Measurement Setup of DPI Method above 1 GHz for ICs,” in Proc. Asia-Pacific Int. Symp. on EMC (APEMC 2013), 2013.
- [6] Op ’t Land S, Perdriau R, Ramdani M, Gil I, Lafon F, Drissi M (2012), “Design of a 20 GHz DPI Method for SOIC8,” in Proc. Int. Symp. on EMC (EMC Europe 2012), 2012, doi: 10.1109/EMCEurope.2012.6396691.
- [7] Auderer G (2005), “High frequency conducted power injection, an alternative measurement methodology to IEC 62132-4 (DPI-method) to test robustness of VLSIs,” LANGER EMV-Technik GmbH, 2005.
- [8] P501/P503 set – RF Power Injection – User Manual, Langer EMV-Technik, Dec. 2021, www.langer-emv.de.
- [9] Levant J L, Gros J B, Duchamp G, Ramdani M (2009), “Resistive RF Injection Probe test Method,” in Proc. Int. Workshop on EMC of ICs (EMC Compo), 2009, pp. 32-35.
- [10] Ayed A, Dubois T, Levant J L, Duchamp G (2009), “A New Method for the Characterization of Electronic Components Immunity,” IEEE Trans. on Instrum. And Meas., vol. 64, no. 9, Sept. 2015, pp. 2496-2503, doi: 10.1109/TIM.2015.2412014.
- [11] AD8302 – RF/IF Gain and Phase Detector – Datasheet – Rev. B, Analog Devices, 2018, www.analog.com.
- [12] EVAL-AD8302 – AD8302 Evaluation Board, 2018, www.analog.com/en/design-center/evaluation-hardware-and-software/evaluation-boards-kits/eval-ad8302.html.