A Method for Measuring Substrate Noise in the UWB Frequency Band on Lightly Doped Substrates

Shen, Ming; Tong, Tian; Mikkelsen, Jan H.; Larsen, Torben

Published in:
Norchip, 2007

DOI (link to publication from Publisher):
10.1109/NORCHP.2007.4481057

Publication date:
2007

Document Version
Early version, also known as pre-print

A Method for Measuring Substrate Noise in the UWB Frequency Band on Lightly Doped Substrates

Ming Shen, Tian Tong, Jan Hvolgaard Mikkelsen and Torben Larsen

Technology Platform Section, Department of Electronic Systems, Aalborg University
Niels Jernes Vej 12, 9220 Aalborg, Denmark
Email: {mish, tt, jhm, tl}@es.aau.dk

***Abstract*—A measurement method for characterizing the substrate noise over the ultra-wideband (UWB) frequency band in UWB systems implemented using lightly doped CMOS processes is presented. The measurement structure in this method is based on modified ground-signal-ground (GSG) pads. In addition, the effects of the distance-based substrate resistance and the capacitive coupling between the substrate and the ground of the measurement setup are evaluated by on-wafer measurement of a test chip fabricated in a 0.18 µm lightly doped CMOS process. An equivalent circuit model of the presented measurement structure is given and shows accurate fit. From the measurement results the presented method is shown to provide a measurement band from 3 GHz to 10 GHz. To further validate the usability of the method a practical class-E PA is used.**

Index Terms—wide band measurements, substrate noise, UWB.

I. INTRODUCTION

UWB communication technology is becoming one of the most promising wireless technologies for the next couple of decades [1]. Due to an advantage in cost and device density, lightly doped CMOS technologies hold a great potential of complying with the needs for implementation of UWB devices. When UWB systems are implemented on a single chip, sensitive RF circuits have to be integrated together with large-scale digital circuits. Those digital circuits will result in the generation of substrate noise in a wide frequency band. Owing to the ultra wide band (larger than 500 MHz within the allocated frequency band from 3.1 GHz to 10.6 GHz) and the low power spectral density of the UWB signal, any substrate noise can easily fall within the UWB operating frequency band and deteriorate the system performance. In order to characterize the substrate noise in UWB systems, a method for the wideband measurement of the substrate noise is one of the most important concerns. So far, a number of studies have been conducted in the characterization of substrate noise [2-10]. The reported studies attempt to address the problem of substrate noise measurement from different perspectives. Some have proposed to verify the coupling model or simulation tools of the substrate [2,3,9]; some have focused on heavily doped CMOS or other integrated circuit processes [5-7]; some have tried to investigate the waveforms or narrow band frequency spectrum of substrate noise [4]; while others have employed complicated circuits or devices as substrate noise sensors [8,10]. However, few publications have investigated a suitable wide band measurement method of substrate noise in UWB systems implemented by lightly doped CMOS processes. The aim of this paper is to present a method for such wideband measurement of substrate noise. A measurement structure based on a modified GSG pad is shown to have high potential to accomplish this. When measuring weak substrate noise, the parasitic components in the practical measurement setup become important and need careful considerations. A test chip is designed using a 0.18 µm lightly doped CMOS process to evaluate the effects of different measurement distances and the capacitive coupling of the substrate and the ground of measurement setups. Several design rules for the application of the presented method are concluded based on the measurement results. An example of measuring the switching noise generated by a practical class-E PA is given to further validate the usability of the presented method.

This paper is organized as following: Section II describes the substrate noise measurement structure. Section III discusses the evaluation of the effects of different measurement distances and the capacitive coupling of the substrate and the ground of measurement setups. Section IV presents the experiment on measuring of substrate noise generated by a two-stage class-E PA. In section V conclusions are drawn.

II. THE SUBSTRATE NOISE MEASUREMENT STRUCTURE

To investigate the substrate noise in a UWB system, the measurement method should have a sufficiently wide measurement band. Besides, it is important to avoid introducing complicated parasitic components or devices in the measurement setup, which can dramatically affect the measurement result and thus provide erroneous information of substrate noise.

The presented substrate noise measurement structure is designed based on a modified GSG pad structure composed of two 85 µm by 85 µm ground pads and one 85 µm by 85 µm signal pad with central-to-central distance of 150 µm. Thus, no extra fixture is needed for measurement of substrate noise using a GSG probe. The cross section view of the structure is shown in Figure 1. It should be noticed that the signal pad is connected to the substrate, and the ground pads are not connected to substrate as usual. There are two reasons behind this:

The project is supported by Danish Research Council for Technology and Production Sciences (FTP).

1-4244-1517-9/07/$25.00 (C)2007 IEEE

1) The substrate noise is weak and therefore it is better to connect the signal pad as directly as possible to the substrate to minimize the loss.

2) If the ground pads are also connected to the substrate, then the measured signal will be the differential mode signal of the substrate noise detected by the signal pad and the ground pads. And it is expected to be very small since the signal pad and ground pads are located close to each other.

Figure 1 also shows the equivalent circuit model of the substrate noise measurement structure. Rtip is used to model the contact resistance associated with probing. The Metal1 ground pad and the substrate is isolated by the oxide layer and build the oxide capacitance that is modelled by Cpad. The capacitance between the signal pad and the ground pad is largely small than Cpad and thus neglected. It is noticed that Cpad is the only reactive component in the model and the bandwidth of the measurement structure is closely related to its value. Its value can be calculated from the oxide thickness and the pad dimensions or from experimental results measured on test structures.

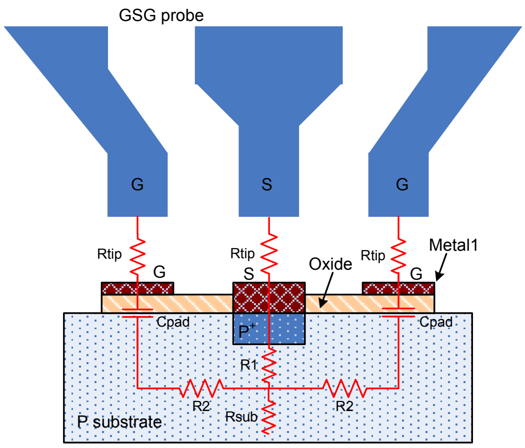

Fig. 1. Cross-section view and the equivalent circuit of the substrate noise measurement structure.

For lightly doped substrates with a resistivity of 20 Ohm-cm, the substrate can not be treated as one single node like heavily doped substrates [7]. To account for this, R1, R2, and Rsub are added to form a simplified resistance network model of the measurement structure. R1 and R2 are used to model the resistance of the substrate below the signal pad and the ground pad. Rsub is used to model the resistance between the substrate noise source to the measurement structure. The values of R1, R2 and Rsub are difficult to estimate and will therefore be derived from experiment setups.

III. Evaluation of Parastical Effects

In the practical measurements of substrate noise, the substrate noise propagating from the noise source to the measurement point experiences attenuation and distortion. Distance-based substrate resistance and capacitive coupling between the substrate and the ground of the measurement setup are two key factors responsible for these effects. In order to obtain the true information on substrate noise, it is necessary to study the effects of them.

A. *Design of the test chip.*

Based on the substrate noise measurement structure mentioned above a test chip is designed to evaluate the effects of distance-based substrate resistance and the capacitive coupling between substrate and the Metal1 ground. Figure 2 shows the topology of the test structure. Four modified GSG pads (denoted by noise detector A, B, C and D) are placed with separating distance of 230 µm, 300 µm and 300 µm, respectively. For each signal pad and ground pad, all the available metal layers from Metal1 to Metal6 are connected. Two wide metal strip lines composed of Metal1 connect ground pads of the substrate noise detectors to produce capacitive coupling between the substrate and the ground of the measurement setup.

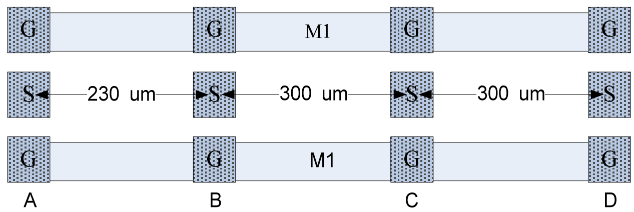

Fig. 2. Topology of the test structure for evaluation of parasitical effects.

Figure 3 shows an equivalent circuit model of the test structure. Here, there are four sub-circuit networks indicated by four dashed squares. Network 1 and 2 are models of the substrate noise detector at port 1 and port 2. Network 3 is the model of the forward coupling network between two measurement ports, including resistive coupling and capacitive coupling. Network 4, composed of Cstrip, R3 and Lstrip, is used to model the coupling between the Metal1 ground strip lines and the substrate. Similar to Cpad in the model of the noise detector, Cstrip can be calculated from the oxide thickness and the strip dimensions or from measurement results. For the test structure, the value of Cstrip can be more than 1 pF. Lstrip is the inductance of the strip line. Generally, the value of Lstrip is small and 1 pH is used in the equivalent circuit.

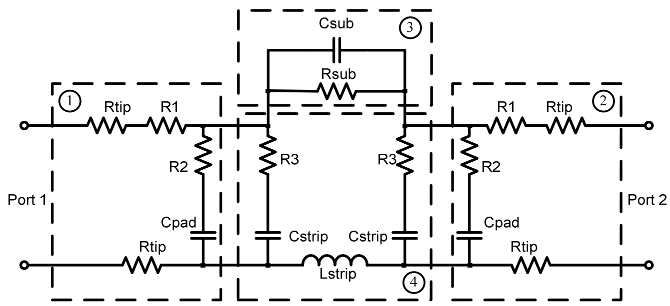

Fig. 3. The equivalent circuit model of the test structure in Fig. 2.

B. *Measurement of the DC resistances*

To determine the distance dependency of the substrate resistance the DC resistance between the different signal pads

1-4244-1517-9/07/$25.00 (C)2007 IEEE

are measured and the results are shown in Figure 4. The DC

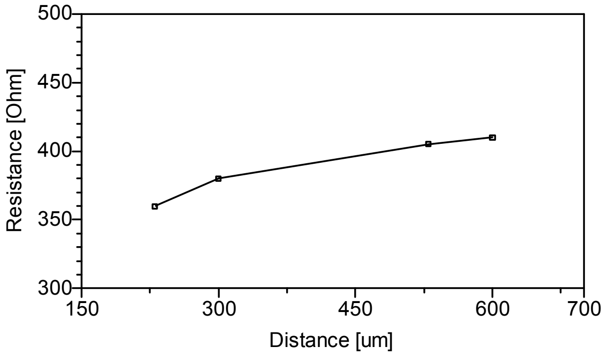

Fig. 4. DC measurement of resistances measured on test structure of Fig. 2.

resistances with distance of 230 µm (AB), 300 µm (BC), 530 µm (AC) and 600 µm (BD) are measured as 360 Ohm, 380 Ohm, 405 Ohm and 410 Ohm, respectively. It is seen that the variation of the measured resistances is not big and there is a trend of the resistance to decrease quicker when distance decreases. This indicates that, for measurement distances from 230 µm to 600 µm, the attenuations caused by substrate resistances are similar. Furthermore, the values of R1 and Rsub in the equivalent circuit of Figure 3 are derived based on these measurement results, and the values of R1 and R2 are approximated as shown in Table I.

TABLE I
PARAMETERS OF THE EQUIVALENT CIRCUIT

Parameters	**Distance**		
	230 µm	**300 µm**	**600 µm**
Rsub (Ohm)	80	100	130
Csub (fF)	30	20	10
Rtip (Ohm)	3	3	3
R1 (Ohm)	140	140	140
R2 (Ohm)	40	40	40
R3 (Ohm)	60	30	10
Cpad (fF)	250	250	250
Cstrip (fF)	1800	2000	2400
Lstrip (pH)	1	1	1

C. S-parameter Measurements

To determine the frequency dependency of the propagation effects, the test chip is studied using S-parameter measurements over 45 MHz to 10 GHz. The measured S21s over 230 µm (AB), 300 µm (BC) and 600 µm (BD) distances are illustrated in Figure 5. The simulation results of the equivalent circuit with parameters in Table I are also shown in Figure 5. From these results the equivalent circuit model is seen to fit measured data very nicely. It is also seen that the attenuations at 45 MHz with different distances are almost identical at -14 dB. For such a low frequency, all capacitive couplings can be approximately treated as open circuit and the attenuation is mainly caused by the substrate resistance. Since the values of the substrate resistances of different distances are similar the attenuations are of course similar too. Moreover, high attenuations of approximately -31 dB, -38 dB and -47 dB are observed over high frequencies for three different distances. From Table I, it is noticed that Rsub, Csub, R3 and Cstrip are the only four changing variables and Csub is insignificant due to its small value. Rsub is also excluded by reason of its similar values of different distances. Thus the different attenuations over high frequencies of three distances must be resulted from different values of R3 and the intentionally built capacitances by the Metal1 strip lines and substrate, i.e. Cstrip. For higher frequencies, coupling through R3 and Cstrip to ground is more pronounced and the magnitude of S21 decreases. From the measured S21 in Figure 5 and the corresponding values of R3 and Cstrip in Table I, it is seen that bigger R3 and smaller Cstrip help to decrease the loss. From Figure 5 the substrate noise detector is found to provide almost constant transfer coefficients over high frequencies. Especially for case 230 µm and 300 µm, the variations of S21 from 3 GHz to 10 GHz are less than 3 dB. In practical applications of the presented measurement method the attenuations can be decreased by decreasing the dimensions of the ground metal planes or increasing the distance between the ground metal planes and the substrate.

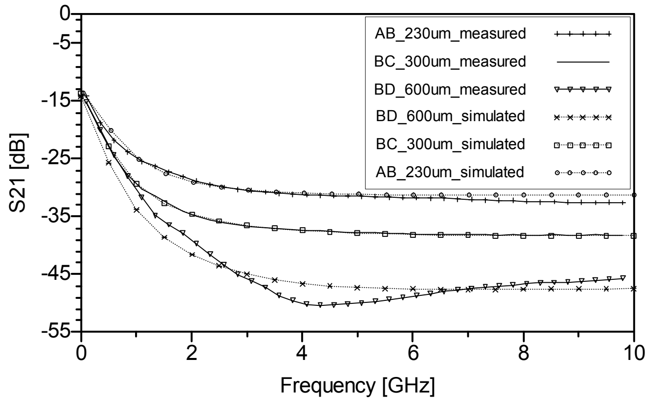

Fig. 5 Simulated and measured S21 of test structures in Fig. 2

Based on the simulated and measured results, design rules of the presented measurement method are drawn as following. Since the attenuations caused by the distance-based substrate resistances for measurement distances from 230 µm to 600 µm are similar, there is no need to put the substrate noise detector too close to the substrate noise source. Furthermore, the effects of capacitive coupling are obvious over high frequencies. To minimize the effects capacitive coupling between the substrate and the ground plane should be minimized.

IV. EXPERIMENT ON MEASURING OF SUBSTRATE NOISE GENERATED BY A CLASS-E PA

As a practical example, the presented substrate noise measurement method is followingly used to measure the switching noise generated by a switch-mode class-E PA. The class-E PA is designed in the same 0.18 µm technology as the test chip in section III and hence all conclusions drawn above can be applied. The PA is composed of two stages working within the Bluetooth frequency band. It has a total gain of 18.6 dB and a maxim output power of 19.1 dBm.

While designing the substrate noise detector on the chip, several factors are taken into account. Firstly, to have a clean reference ground, the substrate noise measurement structure is placed close to the DC ground pad connected to the off-chip DC supply ground. Secondly, for convenient probing, the substrate noise detector is placed at the edge of the chip with a distance of approximately 600 μm to the output stage of the class-E PA. Finally, following the conclusion drawn in section III, to avoid large attenuations, the Metal1 ground plane around the substrate noise detector is deleted to minimize the capacitance between ground and substrate. Figure 6 shows the topology of the chip.

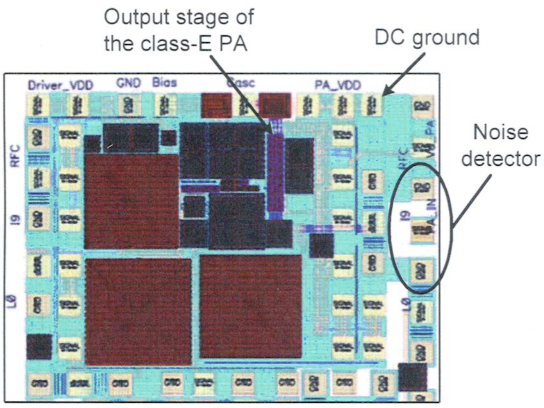

Fig. 6 Class-E PA and the substrate noise detector.

The switching noise is measured when the class-E PA is outputting maximal power. Figure 7 represents the measured frequency spectrum of the switching noise. It shows that the spectral contents of the measured substrate noise appear at 2.44 GHz, 4.88 GHz and 7.32 GHz, i.e. the fundamental and harmonics of the input signal. And the magnitudes of three components are -36 dBm, -72 dBm and -60 dBm, respectively.

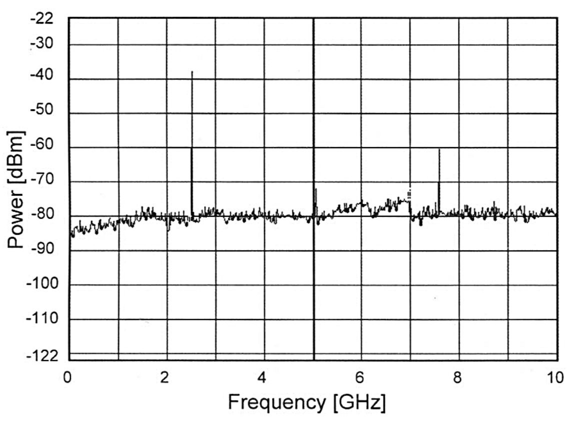

Fig. 7 Frequency spectrum of the switching noise of the class-E PA.

To further validate the measurement method, the spectrum of the drain voltage of the PA's output stage is measured as three discrete spectral components at 2.44 GHz, 4.88 GHz and 7.32 GHz with magnitudes of -12.5 dBm, -49.5 dBm and -35 dBm, respectively. Assuming the drain voltage is coupled to the substrate without big distortions, the attenuations for each component are found to be -23.5 dB, -22.5 dB and -25 dB, respectively. This indicates that the presented method can provide a reliable wide measurement band.

V. CONCLUSIONS

A measurement method is presented for measurement of substrate noises over the UWB frequency band in UWB systems implemented using lightly doped CMOS processes. The effects of the distance-based substrate resistance and the capacitive coupling between the substrate and the ground are evaluated by measurement of a test chip. An equivalent circuit model of the measurement structure is given and shows accurate fit. The simulated and measured results show that this measurement method is able to provide reliable measurements over the UWB frequency band from 3 GHz to 10 GHz. Furthermore, different measurement distances from 230 μm to 600 μm are found to have similar attenuations, while obvious effects of capacitive coupling are observed over high frequencies. To avoid such effects on measured substrate noise the capacitance of the substrate and the ground of the measurement setup should be minimized. Finally, the presented measurement method is validated by measuring the switching noise generated by a practical class-E PA

ACKNOWLEDGMENT

The authors would like to thank Daniel Sira for design of the class-E PA, Yonghui Huang for helpful discussion and Peter Boie Jensen for bonding of the chip.

REFERENCES

[1] F. Granelli, H. Zhang, "Cognitive Ultra-wide Band Radio: A research Vision and Its Open Challenges". Networking with Ultra Wide Band and Workshop on Ultra Wide Band for Sensor Networks, 2005., pp. 55 – 59 July 4-6, 2005.

[2] R. Gharpurey and R. G. Meyer, "Modeling and Analysis of Substrate Coupling in ICs", IEEE Journal of Solid State Circuits, vol. SC-31, n. 3, pp. 344–353, March 1996.

[3] D. K. Su, M. J. Loinaz, S. Masui, and B. A. Wooley, "Experimental results and modeling techniques for substrate noise in mixed-signal integrated circuits," IEEE J.Solid-State Circuits, vol. 28, pp. 420-430, Apr. 1993.

[4] M. van Heijningen, M. Badaroglu, S. Donnay, G. Gielen, and H. De Man "Substrate noise generation in complex digital systems: efficient modelling and simulation methodology and experimental verification," IEEE J. of Solid-State Circuits, vol. 37, pp. 1065-1072, August 2002.

[5] M. Pfost and H. M. Rein, "Modeling and Measurement of Substrate Coupling in Si-Bipolar ICs up to 40GHz", *IEEE Journal of Solid State Circuits*, vol. SC-33, n. 4, pp. 582–591, 1998.

[6] M. Pfost, H. M. Rein and T. Holzwarth, "Modeling Substrate Effects in the Design of High-Speed Si-Bipolar ICs", *IEEE Journal of Solid State Circuits*, vol. SC-31, n. 10, pp. 1493–1501, October 1995.

[7] M. Van Heilningen, J. Copiet, P. Wambacq, S. Donnay, M. Gngels, and I. Bolsens, "Analysis and experimental verification of digital substrate noise generation for epi-type substrates," IEEE J. Solid-State Circuits, vol. 35, no. 7, pp. 1002–1008, Jul. 2000.

[8] K. Makie-Fukuda, T. Kikuchi, T. Matsuura and M. Hotta, "Measurement of Digital Noise in Mixed-Signal Integrated Circuits", IEEE Journal of Solid State Circuits, vol. SC-30, n. 2, pp. 87–92, February 1995.

[9] S. Kristiansson, S. P. Kagganti, T. Ewert, F. Ingvarsson, J. Olsson, and K. O. Jeppson, "Substrate Resistance Modeling for Noise Coupling Analysis", proc. of IEEE ICMTS, pp. 124-129 2003.

[10] R. Gharpurey, "A Methodology for Measurement and Characterization of Substrate Noise in High-Frequency Circuits", in Proc. IEEE Custom Integrated Circuit Conference, pp. 487–491, May 1999.