Near-field electromagnetic characterization and perturbation of logic circuits

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Abstract—We propose here a non-destructive, electromagnetic (EM) near-field test bench both for electromagnetic compatibility and susceptibility of circuits. This set-up permits both the collection of the near-field, and the injection without contact of a disturbing EM field, all through a probe. Exhaustive characterizations of the probes are undertaken via simulations and experiments. According to their design, they are supposedly linked more to the electric or the magnetic field. Simulations of their EM behavior are undergone, so as to fix their optimal geometries leading to the best measurement performances. It is shown, both by simulations and by S-parameter measurements, that their presence does not interfere with the electric behavior of the device under test (DUT). Then logic circuits are characterized from the electromagnetic point of view, with the help of this test bench. Circuits are placed upon three different printed boards: one double sided, low frequency, without a ground plane; two single sided with a ground plane and a design more or less optimized. EM near-field mappings highlight the strong field areas of the circuits. The necessity of a ground plane is highlighted. Field patterns on the traces are linked with those observed on microstrip lines. Then an EM aggression is injected over a supposed sensitive zone of the circuit. Whatever printed board considered, a parasitic signal superimposes itself on the output signal of the gates. Deepened studies are undergone to exhaustively explain the phenomena observed.

Index Terms—electromagnetic compatibility, electromagnetic interference, sensitivity, probe antennas, imaging

I. INTRODUCTION

Electronic components and circuits in operation emit both far-field progressive electromagnetic (EM) waves and confined near-field EM waves \cite{1}. Nowadays, with the drastic circuit integration going on, near-field waves are bound to extend to several circuits at a time and induce their malfunction \cite{2}. For example these fields can be detected by semi-conductor devices such as non-linear junctions, leading to an undesired signal. Though it shouldn't be, this signal will be treated in the same way as any useful signal carrying information. Besides, if the wavelength of the incident near-field wave is of the same order of magnitude as the size of the electronic circuits, it may induce resonance phenomena on the inner connections of the circuit. The usual circuit characterizations, such as TEM and GTEM cells, or S parameter measurements, do not permit the exact identification of the source of electromagnetic waves, hence the analysis of occurring EM problems is not so relevant. Then, it seems particularly useful to characterize in the near-field zone the behaviour of circuits operating in their normal mode in order to localize which are the most disturbing points. Conversely, it is quite interesting to evaluate the effects of these emitted electromagnetic disturbances \cite{3}.

We propose here a non-destructive near-field EM characterization test bench, with application on simple logic circuits. The test bench permits both the collection of the near-field, and the injection of a disturbing EM field. The discussion will be as follows. The test bench and its main elements will be presented in section 2. In section 3, an exhaustive characterization of the probes used will be presented. Then in section 4, EM field mappings undertaken on logic circuits under normal operation will be analysed. Finally, the first results measured on the circuits under an electromagnetic aggression will be highlighted.

II. THE TEST BENCH

The test-bench \cite{4, 5} was developed around the coupling phenomenon of near-field waves with electronic circuits. The device under test (DUT) is fixed to a table mobile in the x, y directions. For EM field mapping, a probe located in the near-field zone sweeps over the surface of the DUT and captures the amplitude of the near-field (Fig. 1). The captured signal goes through a low-noise amplifier (LNA) and is fed to a detection diode or a spectrum analyser. The signal is then processed so as to obtain a DC voltage signal with an amplitude proportional to the power. The voltage, varying between 0 and -1 V, is digitalised by an 8 bit analog-digital converter. A program under Labview then delivers the EM field mapping. For our purpose the test bench operates for frequencies up to 18 GHz. The highest space resolution in the three directions is 1\(\mu\)m.
The remarkable point about this set-up is that it can also be used for the study of the electromagnetic immunity of devices, already mentioned at the Iconic Conference 2007 [6][7][8]. The DUT is kept in normal operation. A high frequency synthesizer is connected to the probe. An electromagnetic interference (EMI) is then produced. The interference signal can hence have varying power, frequency and / or waveform. It is injected through the probe in the chosen near-field area of the circuit. The effect of the EMI is observed by connecting the output of the DUT to an apparatus such as an oscilloscope, or a spectrum analyser. This is a simple, contact-less, non-invasive way of exploring sensitivity of circuits towards electric fields.

Magnetic field probes have the inner conductor bent into a loop (Fig. 2(b)). This time a parallel to ground loop intercepts the magnetic z field component, whereas a loop parallel to the z direction encounters the x-y lines.

The main goal of the experiments undergone on the test bench is to highlight the physical phenomena occurring in electronic devices when these are coupled to EM waves. However, the crucial piece of the set-up is the probe, as the EM wave will be collected by it or injected through it. Simulations of the high frequency probe behaviour were undertaken using the 3-D commercial simulator CST (Computer Simulation Technology) Microwave Studio [10]. We will first concentrate on the optimal geometry of the probes.

The amplitude of the reflection coefficient $S_{11}$ is simulated for several lengths $L$ and several diameters $\phi_{ext}$ of the loop for the magnetic field antenna, cf Fig. 3(b) and 3(c). $S_{11}$ is plotted versus frequency. Results are confirmed experimentally with a vector network analyser (VNA) (Fig.3(a)). For lengths $L$ over 3 mm, resonance peaks appear in the frequency range of study if $L$ is close to a quarter of a wavelength. In the same way a study has been conducted on the magnetic field probe. Resonance peaks also appear when the perimeter of the loop is close to a quarter of a wavelength. However our goal here is that the probe should be broadband and behave in the same way whatever the frequency.

The probe is placed over a microstrip line designed for operation at 10 GHz. This line has a relative permittivity of substrate $\varepsilon_{r} = 3.5$, substrate thickness $h = 1, 6mm$, loss tangent $\tan \delta = 0.002$, line width $W = 4mm$, copper thickness $h_{c} = 35 \mu m$ (Fig. 4(a)). An adapted resistance (50Ω) loads each end of the line. The frequency of the injected EM wave varies from 0 to 20 GHz. Port 1 is on the probe, port 2 at the other end of the line. The transmission parameter $S_{21}$ is simulated on the whole frequency range for lengths $L$ varying from 0 to 6 mm (Fig. 4(b)).

The probes can be placed vertically over the DUT for capturing the z component of the field, whereas it will be placed parallel to the ground for capturing the x–y field lines.
Results show that the influence of the length L on $S_{21}$ is negligible except for the smallest geometry, as shown elsewhere [11]. Taking into account this result and the $S_{11}$ values we chose to keep a length $L = 3$ mm. For the magnetic field probe, an external diameter of $\phi_{\text{ext}} = 2.50$ mm is chosen.

Next we must make sure that the probe intended to measure one or the other of the field component really does so. Simulations have therefore been processed in order to measure the electric or magnetic field components at 1mm away from the probe. An example is given in Fig.5, where the $z$ and $x$ components of the electric field are simulated versus position across the tip of the probe.

For the $z$ component field probe, the amplitude of the $z$ component is largely predominant over the $x$ component for positions right under the probe, that is on the whole outer conductor diameter. Outside this distance the amplitudes both become much smaller with respect to the peak amplitude. The same phenomenon is observed, but with $x$ and $y$ components being predominant, in the case of $x$-$y$ probes. Hence we can really consider that using the appropriate probe configuration the field component chosen is really measured or injected.

We then have assured ourselves that the E field probe would capture essentially the electric field if compared to the magnetic field and vice versa. For this purpose the electric field ratio of the amplitudes of the electric field over the magnetic field has been simulated. An example is shown in Fig. 6 versus distance across the tip of the probe. For the electric field probe, the electric field is predominant, as the ratio $|E|/|H|$ is larger than the vacuum impedance. Equivalent simulations have been performed for the magnetic probe. According to Dyson the loop should be influenced by the electric field [12]. This is confirmed in our simulations as the ratio $|E|/|H|$ is larger than the vacuum impedance value for frequencies above 3 GHz. However for the frequency band of interest for our further measurements, the magnetic probe is sufficiently selective with regard to the electric field, as the ratio value is well under that of the vacuum impedance.

It is now essential to exhaustively characterize the coupling occurring between the DUT and the probe. Most important is the possible influence of the probe on the DUT electric behaviour. For this analysis a high-frequency signal flows through the same micro-strip line presented previously. The probe is placed at various heights above the middle of the line, always keeping it in the near-field zone. The transmission coefficient $|S_{21}|$ between the two ends of the line is simulated versus frequencies varying from 5 to 15 GHz. A first study is first performed with no probe over the line, and for probe heights varying from 0.5 to 2.5 mm over the line. The measurements are also performed on the VNA with the set up and the line in the same configuration. Simulation and experimental results are shown in Fig. 7(a) and Fig. 7(b) respectively.
The biggest discrepancy between curves obtained with and without probes is of 0.1 dB as shown in Fig. 7(a). This very important result is confirmed experimentally as seen on 7(b). The discrepancy measured between curves with no probe or probe at various heights again is less than 0.1 dB. We can therefore assert that the disturbance on the normal behavior of components induced by the probe is negligible. All field mappings and susceptibility measurements will be further processed with the probe fixed at a height of 1.5 mm so as to be in the near-field zone.

In order to put forward the potentialities of the set up for near field measurements, the near field components of both the electric and magnetic fields on a microstrip line have been compared to simulations. The same line designed for a f = 10 GHz operation, is left open ended. For the magnetic field mapping, a loop of 6mm of diameter is used, in order to have an adapted magnetic field probe. Hence the magnetic field is predominant versus the electric field.

The line being left open ended one should observe the presence of standing waves on the line. Indeed characteristic field maxima and minima in field amplitude are observed.

Simulation results, shown in Fig. 8 (a) and (b), are compared to the experimental mapping results (Fig. 8 (c) and (d)) obtained on our test bench. Results are in good agreement with each other. For the electric field, the principle maxima and minima characteristic of the standing waves are located on the line, whereas for the magnetic field they stand on each side of the line. These results will be helpful for the analysis of fields emitted by circuits on circuit boards.

In the next section experimental results concerning electric and magnetic fields emitted by the circuits are presented.

IV. DUT AND NEAR-FIELD ELECTROMAGNETIC MAPPING OF LOGIC CIRCUITS

The DUT HEF4011BP is composed of four commercial logic NAND gates based on a CMOS technology. The schematic is given in Fig. 9.

The gates can operate independently, two by two or all four altogether (cf. Fig. 9). Common data sheets show a maximum operating frequency of 700 kHz for a DC voltage of 5V, and a maximum frequency of 2 MHz for a DC voltage of 15V. For optimal operation of the gates the amplitude of the high-frequency excitation signal should be equal to that of the DC voltage. E and S will respectively design inputs and outputs of the gates. Both for EM mappings and EM aggressions, the gates are always under normal operation.

Gates are placed on three types of PCBs. The first one, circuit A, is designed with logic gates placed on a classical low-frequency double-sided circuit board without a ground plane. The traces of the second and third circuits, circuit B and C, are carried out on only one side of the printed board, the other side is composed of a ground plane. On circuit B gates are connected to each other via jumpers, whilst in circuit C the design is such that there is no need for jumpers.

The logic circuits are DC biased at 15V and are excited with a 2 MHz signal. The outputs are left in an open circuit configuration, or connected to ground if the gates are not under operation. The probe is placed in the near-field zone, at 1mm above the circuits.

The electric field is first considered. For all types of circuits, with and without ground plane, the electric field along the z axis follows the traces of the gates with outputs in open circuit configuration. An example for two gates in operation on circuit C is given in Fig. 10. In this figure, the
loads on each end of the simulated microstrip line symbolise the input and output impedances of the gates. This type of field pattern may come from standing waves induced by the open circuits, as in normal operation the gates are designed for outputs loaded.

The areas where there is a strong field emission are supposed to be the most sensitive to the coupling of EM aggression. Hence in the next section the results are obtained when a high-frequency aggression signal is injected over these sensitive zones.

V. CIRCUIT SENSITIVITY TO THE INJECTION OF AN EM AGGRESSION

The coupling of the electric field is seen to be mostly on the outputs of the circuits, which are of no interest as an injection zone. Therefore we chose to work mainly on the injection of a magnetic field.

For the study of DUT susceptibility, a z-magnetic field component will hence be injected.

The frequency of the injected signal varies from 100 kHz to 1 GHz. DUTs are biased at 5V, the commuting signal is at a frequency of 500 kHz. Two gates are connected with each other and the EM aggression is injected between the output of the first gate and the input of the second gate. The output of the second gate is under observation.

Fig. 13: Parasitic signal measured under a z-field magnetic aggression at f = 456 MHz, (a) on circuit A, (b) on circuit C.

In the 500 kHz - 500 MHz frequency range, a parasitic signal with the same frequency as the aggression superimposes itself on the output signal [6][13]. This result is observed for all three circuits, though the amplitude of the parasitic signal is much larger on circuit A. This highlights again the importance of shielding by the ground plane. Then the fact that a high-frequency signal is observed on circuit A where high-frequency propagation is not encouraged leads to the hypothesis that the circuit pins conduct the aggression.

The localisation of the EMI is also of importance. In Fig. 14 an example is shown where the magnetic field is injected in four different places of the circuit.
In zone (1) there was no field emission whatsoever, and no interference is to be seen. In zones (3) and (4) one can see that the amplitude of the superimposed signal is quite large compared to those observed in zones (1) and (2). This highlights the importance of the coupling of electromagnetic field on the traces. However further investigations must be conducted in order to achieve a list of the most vulnerable points of the DUT.

VI. CONCLUSION

In this paper we present a test bench intended both for electromagnetic field mapping of circuits in the near field zone and for injection without contact of an electromagnetic aggression for susceptibility studies. The principal element of this set-up is the probe which is extensively characterised via simulations and measurements. The optimal dimensions of the probes have been determined. We have shown that the chosen electric or magnetic field component could really be dealt with by using the appropriate geometry. Finally the influence of the presence of the probe on the normal behaviour of a device under tests is negligible.

Logic circuits composed of NAND gates in normal operation are then characterised in the electromagnetic near-field zone with these probes. Mappings of the electric and magnetic field are performed when gates are in operation. These mappings are analysed with the help of results obtained on transmission lines placed on the same test-bench. Magnetic field cartographies on circuits inserted on different printed boards are analysed with the help of results obtained on transmission lines placed on the same test-bench. Magnetic field on the traces. However further investigations must be conducted in order to achieve a list of the most vulnerable points of the DUT.

More deepened studies are now undertaken to analyse this particular point. Another step will be to carry out a systematic and in-depth study of these disturbances versus frequency, amplitude and circuit configuration.

REFERENCES