Low-Cost Broadband Electronic Coupler for Estimation of Radiated Emission of Integrated Circuits in TEM Cell

A. Boyer, S. Ben Dhia

***Abstract*— TEM cell is a well-known method for the qualification of radiated electromagnetic emission from integrated circuits. Combined with a 180° hybrid coupler, it provides a simple method for quantifying radiated emission. However, typical transformer or coupled line-based hybrid couplers have limited bandwidth which cannot cover the full frequency range required by integrated circuit emission tests (150 kHz to 1 GHz). This paper presents the design and the validation of a low-cost broadband electronic version of a 180° hybrid coupler dedicated to the estimation of radiation emission from TEM cell measurements. The proposed prototype is able to cover a large frequency range (from DC to 1 GHz) with a sufficient sensitivity and dynamic range for radiated emission tests in TEM cell. The cost of the presented coupler is very reasonable as it is entirely based on commercial op-amps.**

***Index Terms*—Integrated Circuit, TEM cell, radiated emission measurement**

I. Introduction

TEM cell method, known also as IEC61967-2 [1], is a popular test for the characterization of the radiated emission (RE) of integrated circuits (IC) due to its compact size and its good sensitivity compared to other RE test facilities (e.g. open area test site or anechoic chamber). The typical set-up of TEM cell RE measurement is presented in Fig. 1.a. The TEM cell is a rectangular stripline structure whose dimensions have been defined to ensure 50 Ω matching and transverse electromagnetic (TEM) mode propagation up to 1.2 GHz. Any small powered device placed within the cell excites its TEM mode and induces a voltage on both terminals, which is usually measured by a spectrum analyser.

Actually, the relationship between the measured voltage and RE, for example in free space far-field conditions, is not straightforward. If the excitation source is electrically small and placed at the cell center ($z = 0$), RE can be estimated according to the method described in [2], which is illustrated in Fig. 1.b. The excitation source (here the IC under test) can be expanded into equivalent electric and magnetic dipole moments P_Y and M_X whose RE is easily calculable. They contribute respectively to electric (E) and magnetic-field (H)

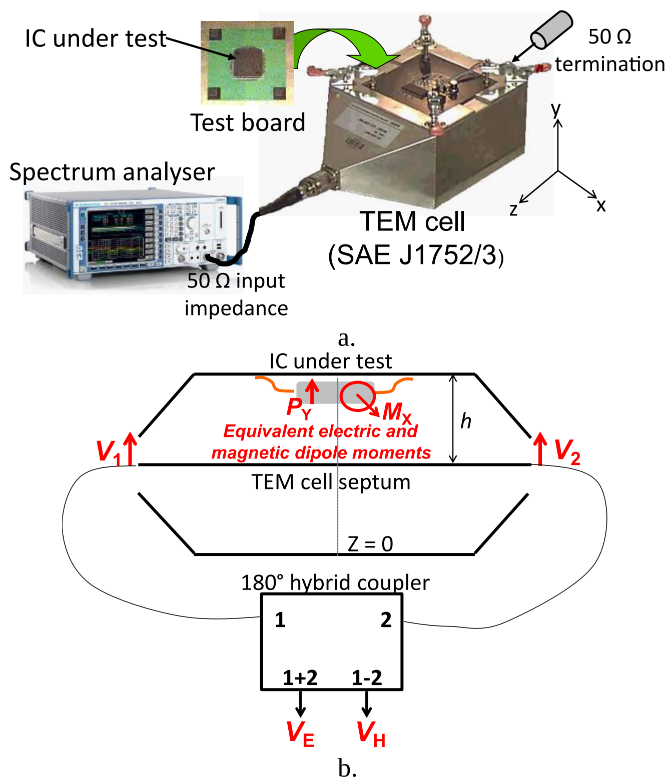

Fig. 1. a. Typical IC radiated emission measurement set-up; b. Extraction of the electric and magnetic-field coupling induced voltages

coupling induced voltages in TEM cell, noted V_E and V_H. The TEM cell termination voltages, V_1 and V_2, are then obtained according to (1) and (2), where k_0 is the propagation constant, Z_C the TEM cell characteristic impedance and h the distance between the IC under test and the TEM cell septum.

$$V_1 = \frac{1}{2}(P_Y + jk_0 M_X)\frac{Z_C}{h} = \frac{1}{2}(V_E + V_H) \quad (1)$$

$$V_2 = \frac{1}{2}(P_Y - jk_0 M_X)\frac{Z_C}{h} = \frac{1}{2}(V_E - V_H) \quad (2)$$

Measuring the voltages V_E and V_H is essential to extract the equivalent electric and magnetic dipole moments. From these figures, not only the RE due to the IC in far-field, but also in

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near-field regions, can be accurately estimated. A typical experimental method to extract V_E and V_H relies on the use of a 180° hybrid coupler as presented in [3], [4] for example. The method is illustrated in Fig. 1*b*. Depending on the frequency range, they are based on transformers, coupled transmission lines or waveguides. However, they never cover the full frequency range required by IEC61967 (150 kHz to 1 GHz), since they usually cover one or two decades of frequency. Moreover, they are expensive devices whose typical costs exceed several hundreds of euros. Surprisingly, in spite of its simplicity, no solution based on active devices has been proposed, certainly because of the required frequency and sensitivity constraints. However, low-cost high-frequency op-amps are available whose frequency and noise characteristics comply with TEM cell test requirements. The purpose of this letter is to present the design and the characterization of a wideband home-made electronic coupler dedicated to the estimation of radiated emission of ICs from TEM cell measurements. Compared to conventional 180° hybrid couplers, the proposed coupler covers a large frequency range (from DC to 1 GHz) which complies with IEC61967 requirements at a reasonable price.

II. Electronic Coupler Design

The proposed coupler is a basic adder and substractor circuit based on the AD8000 op-amp from Analog Devices [5]. This high-speed current feedback amplifier is dedicated to IF/RF gain stage or high-resolution video graphic applications. With a small-signal bandwidth of 1.5 GHz, a high slew rate of 4100 V/µs, a low input voltage noise (1.6 nV/√Hz above 100 kHz), a low distortion (spurious-free dynamic range of 62 dBc at 50 MHz) and an excellent stability, it is a good candidate for the processing of voltage measured at TEM cell terminals.

A home-made prototype has been designed on a two-layer printed-circuit board (PCB). The PCB has not been mounted within a shielded cabinet. The overall cost of the design and fabrication of one prototype is 90 €, which makes it an affordable measurement device. The electrical schematic of the proposed coupler is presented in Fig. 2. Although its principle is simple, a careful design is required. The length of PCB traces must be limited and keep symmetrical to reduce parasitic output capacitance which may compromise stability and limit phase error. IEC61967-2 standard requires a voltage standing wave ratio (VSWR) less than 1.5:1, i.e. an input reflection coefficient less than -14 dB. SMA coaxial connectors are mounted at input and output terminals. The input impedance of the coupler must be controlled to ensure sufficient 50 Ω matching, because of the capacitive behaviour of the op-amp inputs (typically 3.6 pF).

The choice of resistors is a compromise between stability, gain flatness and minimization of noise. In this design, identical 330 Ω resistors are used so that the overall gain of the coupler is equal to 1. The output noise is estimated to 17 nV/√Hz above 100 kHz, i.e. -5 dBµV with 1 kHz RBW receiver, which is equivalent to noise floor of typical spectrum analyser. As the gain of the input stage of the coupler is equal to 2 and the maximum output voltage swing of the op-amp is 2V, the largest measurable signal at the input is equal to 1 V. The dynamic range between the largest and lowest harmonics of the input signal is limited by the distortion introduced by

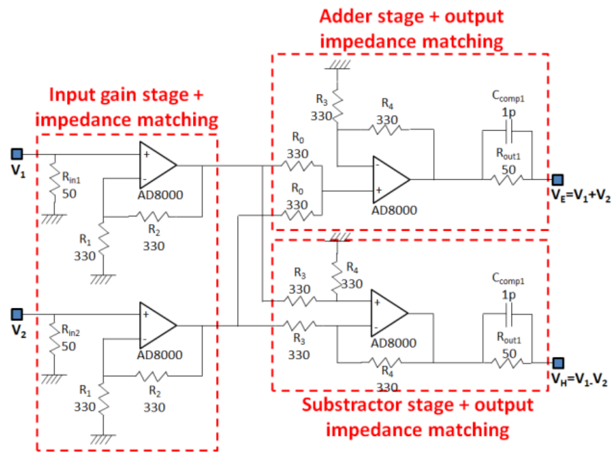


Fig. 2. Schematic of the proposed electronic coupler

the op-amp. Below 100 MHz, the dynamic range exceeds 50 dB. As typical IC emission levels seldom exceed 50 dBµV, the dynamic range and the noise of the proposed electronic coupler comply with the requirements of the TEM cell measurement. This coupler has also other advantages compared to transformer or stripline-based hybrid couplers: it provides an excellent isolation between output terminals and there is no coupling loss between input and output. Moreover, the gain can be adjusted and increased, but it results in a reduced cut-off frequency.

III. Experimental Characterization

The performances of the designed prototype have been characterized. In order to prevent external interference issues, all the tests have been made in a Faraday cage. The reflection coefficients of both inputs have been measured, as shown in Fig. 3. They are less than -20 dB except between 800 MHz and 1.2 GHz, but they do not exceed the -14 dB requirement.

The noise introduced by the coupler has been characterized by measuring the noise floor of the spectrum analyser (Keysight N9341C) with and without the electronic coupler. Without the coupler, with a resolution bandwidth of 1 kHz, the noise floor of the spectrum analyser is -5 dBµV. With the coupler, it rises about 4 dB. If we suppose that the noise voltages produced by the spectrum analyser and the coupler are gaussian and uncorrelated, the amplitude of the noise introduced by the coupler can be estimated to -3.3 dBµV, which is acceptable for typical TEM cell emission measurements.

Correct sum and difference operations requires a small gain and phase differences between both signal channels. It depends on the design symmetry. The gain difference between signal channels is less than 2 dB up to 1 GHz, while the phase difference is less than 20°. Fig. 4 illustrates the frequency response of the sum and difference channel. The -6 dB cut-off frequency is reached at 1.01 GHz and 1.1 GHz. The gain is constant from DC to 100 MHz and varies in the range 100

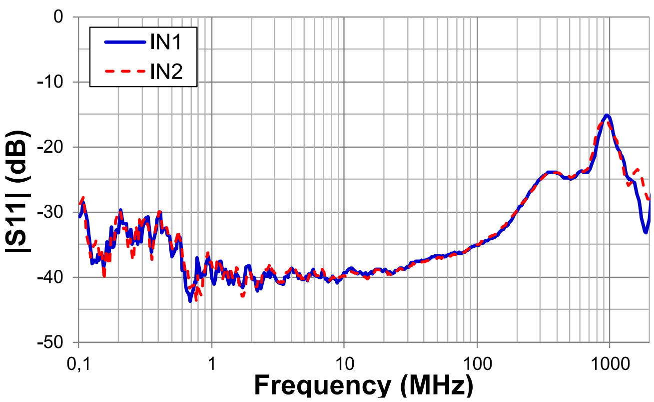


Fig. 3. Characterization of the reflection coefficient of coupler inputs

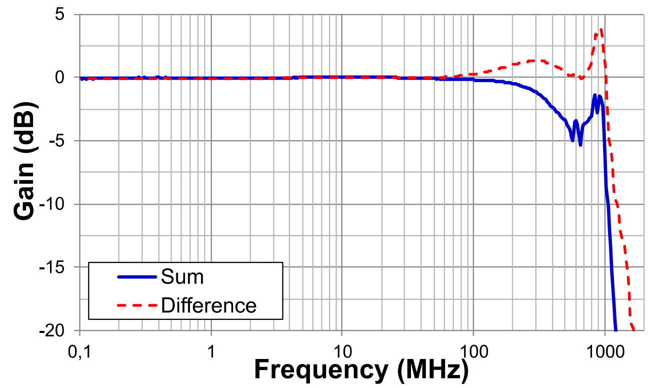


Fig. 4. Characterization of the gain of the sum and difference channels

MHz to 1000 MHz, according to the choice of resistor values and an optional compensation output capacitor. Only a compromise between gain flatness and bandwidth can be found. However, the gain fluctuation can be characterized for calibration purpose.

IV. Validation Case

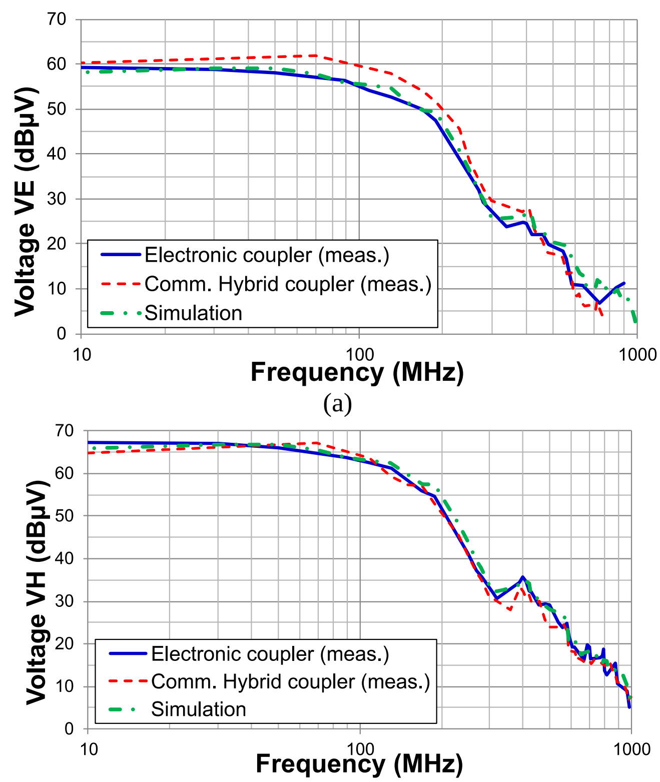
In order to validate the results delivered by our electronic coupler, the E and H field coupling induced voltages V_E and V_H are measured with a spectrum analyser (Keysight N9341C). The device under test is a 75 mm long 50 Ω microstrip line excited by a 10 MHz square signal with 4 ns transition time and a duty cycle of 50 %. The line ends are terminated by either 50 Ω load, shorted or opened. Depending on the line loading, electric, magnetic field, or both fields are predominant in near-field region. For comparison purpose, measurements are also performed with a commercial 180° hybrid coupler (model ET Industries J-053-180) whose bandwidth is 500 MHz to 3000 MHz. Finally, measurement results are compared with the predicted values of V_E and V_H. The prediction relies on (3) and (4) [6], which gives the electric and magnetic field coupling due to the equivalent electric and magnetic dipole moments P_Y and M_X of the line which is supposed electrically short.

$$V_E(f) = P_Y(f)\frac{Z_C}{h} = j2\pi f c_{line} V_{line}(f)\frac{Z_C l_{line} h_{line}}{h} \quad (3)$$

$$V_H(f) = j\frac{2\pi f}{c_0} M_X(f)\frac{Z_C}{h} = j\frac{2\pi f}{c_0} I_{line}(f)\frac{Z_C l_{line} h_{line}}{h} \quad (4)$$

where f is the frequency, l_{line} and h_{line} are the length and the height of the microstrip line, c_{line} its per-unit-length capacitance, and V_{line} and I_{line} the measured excitation voltage and current of the line. A Scilab script was developed to compute V_E and V_H voltages. The model was previously validated by comparing simulation results with S-parameter measurements between the line under test and the TEM cell. A good agreement was observed up to 1 GHz.

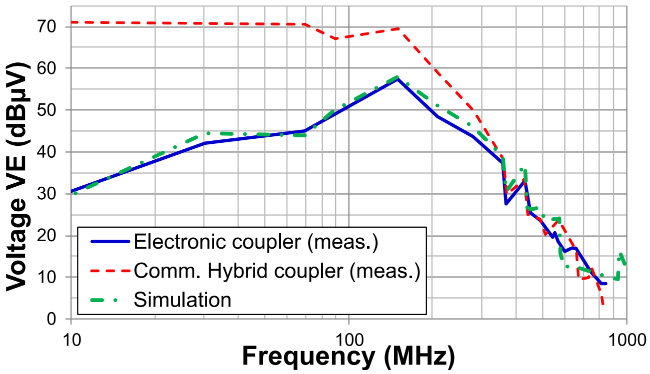
Initially, the line under test is terminated by a 50 Ω load. Measurement and simulation results of V_E and V_H voltages are compared in Fig. 5. For readability, only the envelop of emission spectra are plotted, which presents the maximum values taken by the spectrum. The measurements done with the proposed coupler fit with simulation, proving the validity of the measurements done with the proposed coupler up to 1 GHz. They also fit with the measurement done with the commercial 180° hybrid coupler in the range 500 MHz to 1 GHz.



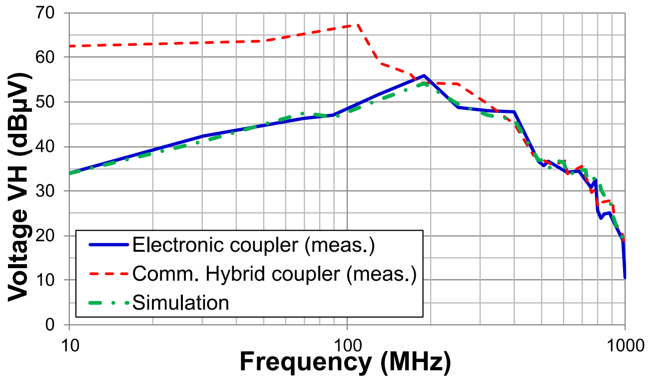
(b)

Fig. 5. Line under test terminated by 50 Ω. Comparison between measurements with the proposed electronic coupler, a commercial 180° hybrid coupler and simulation of: (a) E-field coupling induced voltage V_E, (b) H-field coupling induced voltage V_H

Two other configurations are tested: either the line under test end is opened to enhance E field and limit H field generation, or the line under test end is shorted to enhance H field and limit E field generation. Measurement and simulation results of V_E and V_H voltages are compared in Fig. 6. In the top figure, the line under test is shorted and the E field coupling induced voltage is captured. In low frequency, as long as the



(a)



(b)

Fig. 6. Comparison between measurements with the proposed electronic coupler, a commercial 180° hybrid coupler and simulation of: (a) Line under test terminated by a short. E-field coupling induced voltage V_E, (b) Line under test opened at its end. H-field coupling induced voltage V_H

line is electrically small, the voltage V_E remains negligible as shown by the measurement done with the proposed electronic coupler and the simulation, which are in good agreement. In this situation, results provided by the commercial coupler are false up to 300 MHz since it is used outside its nominal frequency range. Above 500 MHz, measurements made with both couplers are also in agreement. Fig. 6 (bottom) presents similar results for the voltage V_H when the end of the line is opened. The induced voltage due to magnetic field coupling remains negligible in low frequency. Measurements with the proposed electronic coupler are in good agreement with the simulation results, and with the measurement results obtained with the commercial 180° hybrid coupler between 500 MHz and 1 GHz.

V. Conclusion

In this letter, an electronic version of a 180° hybrid coupler has been designed in order to separate the contributions of electric and magnetic field coupling in emission measurement of ICs in TEM cell. This type of measurement is essential to estimate the radiated emission of ICs not only in far-field but also in near-field conditions. Compared to typical transformer or coupled line-based hybrid coupler, the proposed coupler relies on low-cost off-the-shelf op-amps. It covers all the frequency range required by the emission standard test IEC61967-2 (150 kHz to 1 GHz), without any excessive degradation of noise floor of the measurement receiver.

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