Toward Co-Design of Spin-Wave Sensors with RFIC Building Blocks for Emerging Technologies

Q.H. Tran[1], S. Wane[2], F. Terki[1], D. Bajon[3], A. Bousseksou[4], J. A. Russer[5], and P. Russer[5]
[1]ICGM-CNRS Montpellier, [2]eV-Technologies Caen-France, [3]ISAE-SUPAERO Toulouse-France
[4]LCC-CNRS, Toulouse, [5]Institute for Nanoelectronics, Technische Universität München, Germany

***Abstract*— A holistic approach is proposed for Chip-Package-PCB-Probe Co-Design of near-Field and far-Field detectors for the test and characterization of emerging technologies. Innovative integrated Magnetic Sensor solutions at micronic and nanometric scales are presented. Several sensor architecture topologies are designed, fabricated and experimentally characterized in terms of their performances for several applicative scenarios. Perspectives for Co-Design of Spin-Wave sensors with RFIC building blocks are drawn. Designed and fabricated unit-cell Spin-Wave magnetic sensors exhibit Nano-Tesla accuracy outperforming, at room temperature, state of the art magnetic sensors based on Hall effects, Squid technology or Josephson junctions. Dedicated prototypes are realized for proper co-integration of the magnetic sensors with CMOS/BiCMOS/SOI electronic circuitry including biasing, control and signal processing which support DC and RF/mm-Wave sensing.**

Index Terms*— *Chip-Package-PCB-Probe Co-Design, Near Field scanning, Magnetic Sensor, Spin-Wave Technologies, Hybrid Planar Hall Magneto-Resistive sensor, Nanostructured Multilayers.

I. Introduction

Magnetic sensors are key enablers for both near-field and far-field detections [1-11] of intentional and nonintentional (noise) radiations. In order to push magnetic sensors to their ultimate thermodynamic performances in terms of sensitivity and multi-physics attributes Spin-Wave [12-15] based technologies are required.

Beyond the specific application of near-field and far-field detections, Spin-Wave technologies will foster new paradigms. These paradigms will enable Energy-based Co-design [11] tradeoffs driving innovative applications relative to new instrumentation [16] technologies and to interactions of humans with smart devices in randomly changing environments. Spin-Waves are envisioned to augment CMOS/BiCMOS/SOI circuits and to open extended Moore's law well beyond the actual scaling limits. Fig.1 displays the Moore's law scaling of conventional CMOS, BiCMOS-SiGe, GaAs and SOI technologies underlining the decaying power supply voltage as operating frequency increases.

In this paper, Chip-Package-PCB-Probe Co-Design of near-field and far-field detectors for the test and characterization of emerging technologies are considered following a holistic approach. Designed, fabricated and experimentally characterized innovative integrated magnetic sensor solutions at micronic and nanometric scales are studied and their architecture topologies are discussed in terms of their performances. Perspectives for Co-Design of Spin-Wave sensors with RFIC building blocks are drawn from designed and fabricated unit-cell Spin-Wave magnetic sensors. The proposed Co-Design of Spin-Waves with RFIC building blocks paves the way toward photonics-based co-integration solutions.

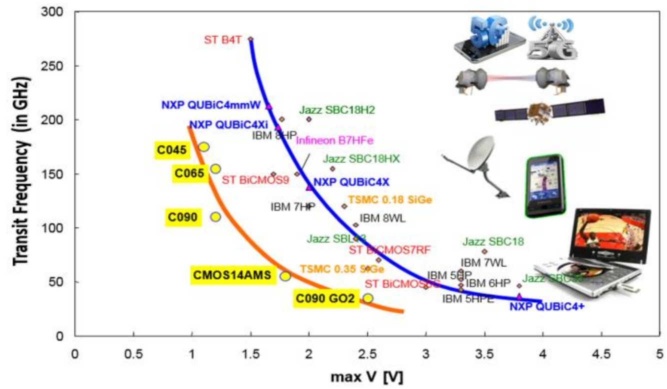

Fig.1: Transit frequency as function of maximum power supply voltage for state of the art technologies: S. Wane et al. "*Design of Lange Couplers with Local Ground References using SiGe BiCMOS Technology for mm-Wave Applications*", in Proc. of IEEE RFIC 2015.

The paper is built around two main sections. In the first section, near-field measurement solutions for stochastic electromagnetic fields are presented. State of the art Single-Probe, Dual-Probe and Multi-Probe (Array) based near-field measurement techniques are evaluated for the characterization of emerging 5G and IoT applications. Chip-Package-PCB Co-Design approach is proposed for high spatial resolution of Multi-Probe near-field scanning systems with controlled sensitivity and noise uncertainties using RF and mm-Wave manufacturing solutions namely using Bond-Wire Arrays and Wafer-Level-Chip-Scale-Packaging (WLCSP). The second section draws perspectives toward Co-Design of Spin-Wave Sensors with RFIC Building Blocks for emerging technologies. Spin-Wave Co-Design is expected to enable new co-integration solutions of CMOS/BiCMOS/SOI RFICs beyond Moore's law scaling.

II. Main Experimental Investigations

A. *Chip-Package-PCB-Probe Co-Design & Co-Analysis for Test and Characterization of Emerging 5G Technologies*

Power Integrity (PI), Signal Integrity (SI) and EMC/EMI requirements represent the bottlenecks of present and next generation communication systems towards higher data rate, low consumption and immunity to unwanted disturbances. Near-Field measurement of radiated emissions from Chip-Package-PCB-Antenna circuits and systems is mainly motivated by the following objectives:

1) Verification of EMC/EMI compliance for product evaluation and qualification (c*ertification-oriented*).
2) Diagnosis of Power Integrity (PI), Signal Integrity (SI) and EMC/EMI problems for design improvement (*Debug-oriented*).

Beyond the classical EMC/EMI compliance evaluations essentially based on Pass/Fail certification approach, there is an increasing demand for use of Near-Field measurement solutions for diagnosis purposes with loop-back to modeling analysis for design improvement. Including Near-Field measurement verifications as part of conventional product design, development and evaluation procedures will be decisive in ensuring First-Time-Right success target with reduced Time-to-Market.

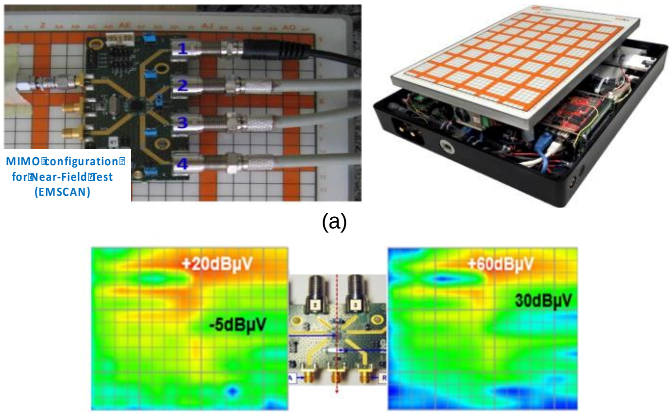

Fig. 2 Measured radiated Near Field distribution (b)-(c) from Chip-Package-PCB circuit using *EMSCAN* Multi-Probe (array) scanner (a).

Recent progress in electronic technologies together with the advent of modern signal processing techniques have led to the proliferation of increasingly faster, accurate and cost-effective Near-Field scanning systems. However, the effective use of available Near-Field scanning systems, in the context of industrial applications, remains limited by throughput Test-time, reliability constraints and reproducibility of measurement results.

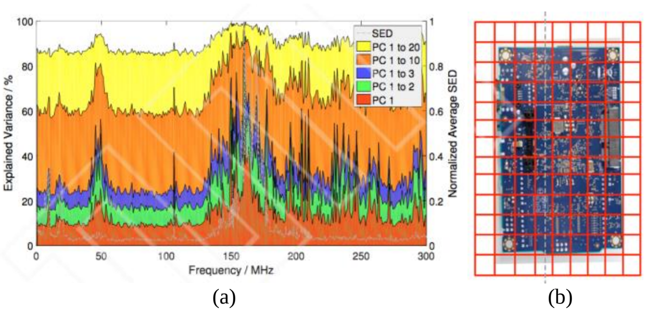

Fig. 3 Measured Spectral Energy Density (SED) and variance (a) as function of cumulative principal components using Dual-Probe scanner in time domain [9] of Galileo microcontroller board based on the 400 MHz Intel Quark SoC X1000, a 32-bit Intel Pentium class system on chip and the scanning grid used on an area of 9cm x 13 cm domain (b).

A proposal for standardization of Near-Field measurement of Stochastic [1-4] Electromagnetic Fields led by the European *COST Action 1407* [3] has been initiated. This initiative has resulted in an *IEEE* standard being specified for Single-Probe, Dual-Probe and Multi-Probe scanning systems. The Single-Probe, Dual-probe and Multi-Probe based measurements are compared in terms of their RF, accessible resolution, reliability (including mechanical stress) performances and Test-time for industrial deployment.

Main technical challenges include the following assessments:

- Attributes of Time-Domain versus Frequency-Domain measurement solutions.
- Effects of Probe-System/DUT interactions on measurement accuracy.
- Requirements for stochastic EM field measurements.
- Simulation and measurement complementarities.

Fig.3(a) depicts the measured Spectral Energy Density (SED) as function of cumulative principal components measured in time domain using Dual-Probing system. It is observed that more than 90% of the Spectral Energy Density is carried by the first ten principal components. This opens new perspectives for complexity reduction by filtering and/or principal component analysis (PCA) of the near field distribution.

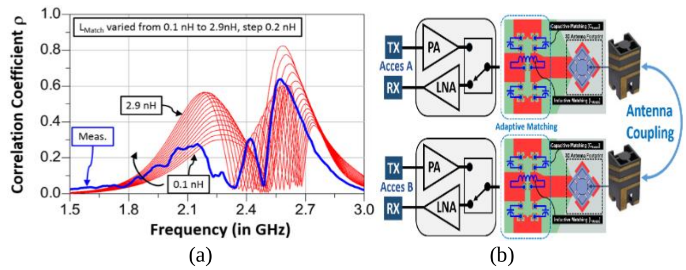

Fig.4: Full-wave EM simulation of MIMO antenna correlation as function of frequency for different matching networks compared to measurement (a). MIMO setup using 3D Antenna-In-Package and Front-End-IC modules (b).

Fig.4 shows coupled MIMO [7] antennas cross-correlation as function of variable matching network combined with front-end-ICs for 5G communication. The extracted cross-correlation can be linked to the general theory of coherence [8], [1].

For magnetic field detection, loops are conventional probing systems available in baseline IC-process technologies using bond-wire arrays. Different configurations in Ground-Signal-Ground probing system are presented in Fig. 5(a),(b),(c),(d) for systematic analysis of bond-wire arrays extraction parameters: e.g., self-inductances, mutual couplings, Estimated-Series-Resistances (ESR), Insertion-Loss (IL), Return-Loss (RL).

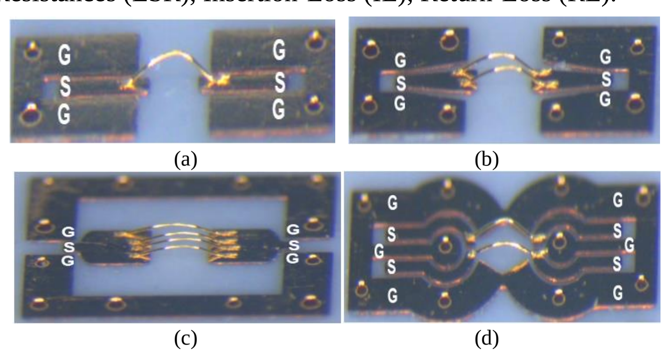

Fig. 5. GSG (a),(b),(c) [two-port] and GSGSG (d) [four-port] configurations for experimental characterization of bond-wire arrays with variable wire profiles.

The Bond-Wire loops in the order of 100μm equi-spaced by a separation distance less than 40μm define the achievable spatial resolution. Improved spatial resolutions can be achieved with advanced WLCSP technologies. Prototype design have shown in [17] promising performances when On-Chip Low-Noise-Amplifiers (LNA) are co-designed with Bond-Wire loop sensors implemented at package level. In Fig.6(a) the variation of self-inductance and ESR of a Bond-Wire array as function of the number of its wire elements is provided. These values obtained from measurement and EM simulation are in a good agreement for operating frequencies up to 50GHz. All of them are reduced by increasing the number of BW. However, this reduction shows nonlinear behavior with saturation effects induced by couplings between wires. Fig.6(b) and Fig.6(c) show effects of loss-tangent (tan(δ)) and bond-wire profile on mutual coupling parameters as function of frequency which highlight the importance of controlled process variations both for the material properties and bond-wire profiles.

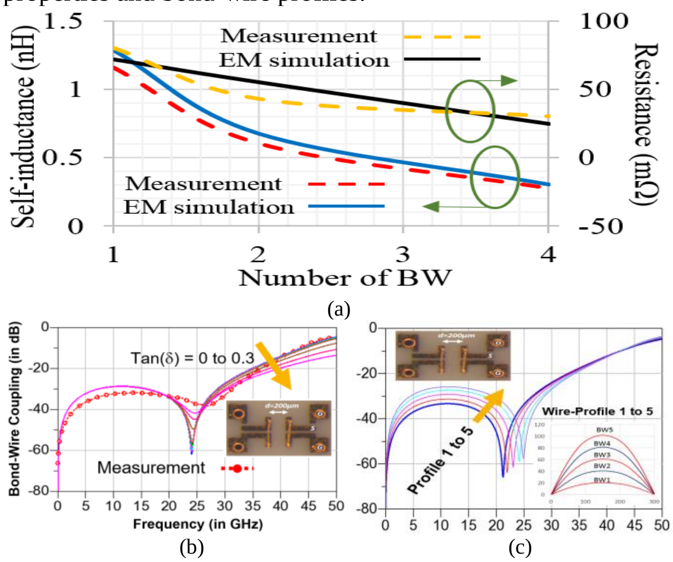

Fig. 6: Self-inductance and resistance as function of the number of bond wire (BW) elements (a). Effects of loss-tangent (tan(δ)) and wire-profile (P1, P2, P3, P4, P5) on bond-wires couplings.

B. Toward Co-Design of Spin-Wave Sensors with RFIC Building Blocks for Emerging Technologies

In this section we present innovative integrated Magnetic Sensor solutions at nanometric and micronic scales for emerging communication technology applications [12-15]. Compared to state of the art magnetic sensors, the proposed solution exhibits the following attributes:

- Compacity for co-integration with active circuitry.
- Low-Power biasing free operating conditions.
- High accuracy detection in the order of nano-Tesla variation
- Ultrasensitive Magnetic Local probes with high spatial resolution within the nanoscale range.
- Small temperature drift and high stability performances in the detection for temperature variations from (4K - 473K)

Table I reports state-of-the-art magnetic sensors as function of detectable field range and used technology. Compared to state of the art SQUID-based technologies, which can only operate below few tens of Kelvin, the proposed solution is operational at room temperature with four order of magnitude improvement over Quantum Design SQUID at its highest sensitivity condition [12-15].

TABLE I: State-of-the-art of Magnetic Field sensitivity and Temperature operating for range magnetic sensors including superconducting quantum interference device (SQUID), Flux gate sensor, Giant Magneto-Resistance (GMR) sensor, Hall Effect sensor, and Planar Hall Magneto-Resistive (PH-MR) sensor.

MAGNETIC SENSOR	DETECTABLE FIELD RANGE				
	1 fT	**1 pT**	**1 nT**	**1 µT**	**1 mT**
SQUID	mKelvin-70K micro SQUID		4-300 Kelvin SQUID Quantum Design		
Flux gate		300Kelvin (Km of length)			
GMR sensor			300Kelvin (micron/mm size)		
Hall effect sensor				300Kelvin (micron-size)	
PH-MR sensor (*)		4-473Kelvin (micro size)			
Earth field				300K	

(*) *Field sensitivity of magnetic sensor achieved in this work*

Ultrasensitive Near-Field EM detection combined with high spatial resolution in nanometer scale has been developed (pTesla and 10^{-14} emu at 300K) and verified experimentally. The topology of the PH-MR 300 x 300 mm² designed for low frequency applications is shown in Fig.7 (a) with its amplifying and signal conditioning circuitry, exhibiting a noise around or less than $1nTHz^{-1/2}$ while 350 pT are detected repeatedly via synchronous detection as shown in Fig. 7 (c).

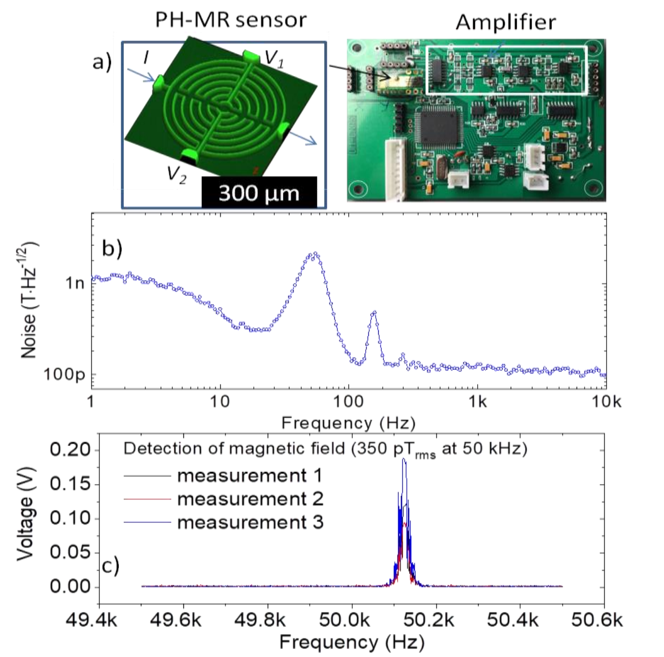

Fig. 7: Magnetic near-field probes (a) based on a PH-MR sensor and amplifier, noise profile (b) of a PH-MR sensing probe. The noise as low as $100\ pT/Hz^{-1/2}$ is achieved for the probe size of 300 µm. Magnetic field measurement (c) of PH-MR probes at $1nT_{p\text{-}p}$ as repeated with three different sensors.

The proposed approach is based on hybrid Planar Hall Magneto-Resistive PH-MR nanostructured multilayers. The optimization of nanostructured magnetic multilayers together with the architecture design of the sensor enables the development of magnetic detectors with nano-Tesla measurement accuracy [12-15]. The obtained detection accuracy opens perspectives for new applications ranging from medical imaging/diagnosis to emerging RF, mm-Wave and optical applications.

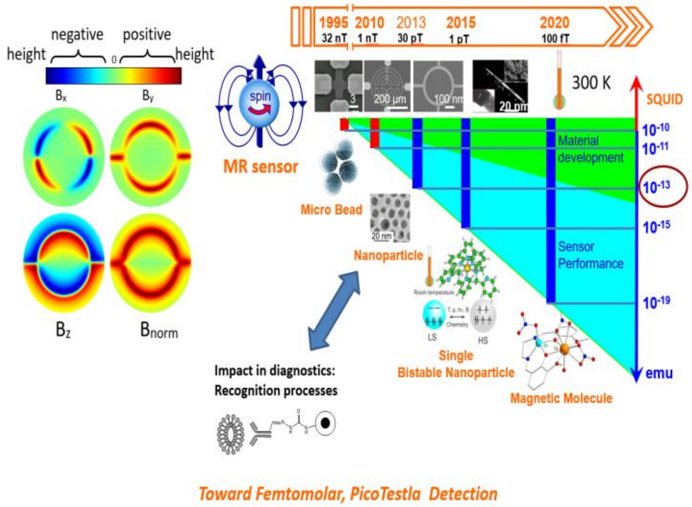

Fig.8: Projected roadmap technologies for Near-field and far-field EM detection based on magnetic micro-sensing probe (Numerical simulations and experimental achievements [12-15]).

Perspectives for co-design of spin-wave sensors with RFIC building blocks will result in the development of innovative magnetic scanning systems with two major specifications (i) very high sensitivity performances, and (ii) scanning in a wide frequency range up to millimeter-waves and beyond including DC component. To achieve the targets drawn in the roadmap in Figure 8, Chip-Package-PCB-Probe (Antenna) is crucial for development of sensitive magnetic probe systems.

III. Conclusion

Experimental characterization of radiated emissions from RFIC circuits in presence of noisy sources assessed as function of input power levels exhibits ultimate sensitivity limit [17] evaluated to be around -130 dBm to –135 dBm. Pushing detection sensitivity to ultimate accessible performances requires a holistic Chip-Package-PCB-Probe Co-Design. For stochastic radiated emissions, it is established [2] that numerical values of noise amplitudes cannot be specified. Thus, for modeling and measuring stochastic signals, it is required to deal with energy and power spectra based on the extraction of Field-Field correlation functions. Perspectives for Co-Design of Spin-Wave [12-16] sensors with CMOS/BiCMOS/SOI RFIC building blocks are drawn from designed and fabricated unit-cell Spin-Wave magnetic sensors exhibiting nano-Tesla accuracy outperforming, at room temperature, state of the art magnetic sensors based on Hall effects, Squid technology or Josephson junctions. Spin-Wave Co-Design with RFICs is expected to enable new co-integration solutions beyond Moore's law scaling toward low-power and high sensitivity far below the -135dBm limit observed with conventional Si-based Bond-Wiring and WLCSP process technology solutions. Adoption of Energy and Entropy [11] metrics as standard assessment of emerging technologies will push their thermodynamic performances to ultimate limits by allowing 3D [18] Multiphysics (*e.g., Thermal-Electromagnetic cross-correlation analysis*) Co-Design handling of *Density of States*, Energy and Entropy metrics.

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