Concurrent Circuit-Level/System-Level Optimization of a 24 GHz Mixer for Automotive Applications Using a Hybrid Electromagnetic/Statistical Technique

Francesco Placentino[1], Daniela Staiculescu[2], Symeon Nikolaou[2], Lara Martin[3], Andrea Scarponi[1], Federico Alimenti[1], Luca Roselli[1], Manos M. Tentzeris[2]

[1]Dept. of Electronic and Information Engineering, University of Perugia, 06125 Perugia, Italy

[2]GEDC, School of ECE, Georgia Institute of Technology, Atlanta, GA, 30332, U.S.A.

[3]Motorola, Plantation, FL, 33322, U.S.A.

Abstract — **The successful use of the Design of Experiments (DOE) and Response Surface Methods (RSM) approaches in the simultaneous optimization of geometrical parameters and power requirements of a 24 GHz mixer is presented. The benchmarking geometry is a low-cost mixer for a Doppler Radar Sensor, built in Liquid Crystal Polymer (LCP) technology. First, the single-balanced diode mixer is designed for good RF/LO isolation and low conversion loss. The structure is then optimized using the same experiment that integrates both geometrical parameters and the LO input power levels. The optimized mixer shows a 4.5 dB conversion loss with a 23 dB isolation between RF and LO ports at the operating input power levels, the best reported so far for this frequency range and in these operating conditions.**

Index Terms — **Automotive radar, mixer, hybrid/concurrent optimization, statistical tools, electromagnetic design.**

I. Introduction

In the recent years, the fast growth of traffic congestion yielding to an increasing number of car accidents has increased the need for higher traffic control efficiency and driver safety [1]. This has raised the interest of automotive industry in developing a number of active and passive systems to enhance road safety. A Doppler radar sensor can easily measure both the true ground speed of the vehicles and the relative speed between a car and an obstacle and can be used to reduce reaction times, avoid accidents or simply monitor a high traffic road. The allocated band for these sensors is the ISM 24 GHz, sharing the spectrum with other wideband services [2].

The homodyne Doppler radar sensor architecture employs only one step for the down-conversion from RF to baseband. In this case the performance of the mixer is very important. In our design, we used an inexpensive single balanced diode mixer in rat-race configuration to reject the AM noise of the oscillator. The mixer was designed in Advanced Design System (ADS) and it was found that the following factors are affecting its performance: First, the input matching at the LO port is critical for setting the specified input LO power level [3].The length of the input LO stub is expected to affect the conversion loss at the operating frequency. Second, the load resistance R_L guarantees the maximum power transfer at the IF frequency and affects both the conversion loss (CL) and the isolation between RF and LO ports.

The length of the input LO stub and the value of the load resistance R_L representing the circuit level, as well as the LO input power level representing the system level, are incorporated into the Design of Experiments (DOE) and Response Surface Method (RSM) statistical optimization techniques, which give a thorough understanding of the system and, most importantly, give information such as how these performances are affected by each other, namely how they interact. Previous work [4] shows successful use of hybrid statistical techniques in microwave system analysis and optimization, but this is the first reported work on incorporating the circuit and system levels into the same co-simulation. The system is optimized with respect to all these factors simultaneously, also giving the designer the flexibility to choose the goals and the weights of each of the optimized outputs. Additionally, this flexibility makes possible to predict the performance of multi-level systems, by separately analyzing each level and then combine them all together in any desired way by using output variables for lower level as inputs for the next level.

II. Radar Sensor

The benchmarking structure is a down-conversion diode mixer, a building block of the Doppler radar sensor presented in Fig. 1.

The continuous waveform signal is generated using a Dielectric Resonator Oscillator (DRO), then a Wilkinson power divider splits the signal into two equal parts, one feeding the transmission channel (power amplifier and transmission antenna) and another the receiving channel (local oscillator). The signal reflected back from the target, which contains the information about the radial velocity of the target itself through the Doppler shift, is divided after the Low Noise Amplifier (LNA) and then fed into the RF ports of the down-conversion I (phase) and Q (quadrature) mixers. The I/Q configuration of the receiver is necessary in order to detect the direction of motion [2].

1-4244-0688-9/07/$20.00

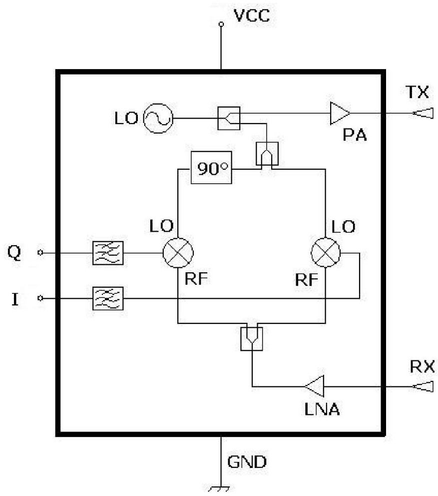

Fig. 1. Architecture of the Doppler radar sensor

The LCP mixer was designed in Advanced Design System (ADS) and Fig. 2 shows a picture of the layout. The diodes and the resistor are surface mounted, and the low-barrier diodes MA4E2502L have been chosen such that there is no need for DC bias, namely the levels of the RF and LO signals are enough to turn them on. The placement of the RF and LO ports is critical for the conversion loss performance [5]. The conversion loss of the mixer is also affected by the length Lstub_LO of the input stubs next to the LO input, designed to maximize the available power at the input port of the mixer. The mixer operates in the linear zone, with input power levels in the interval of P_{LO} [1 mW, 2.5 mW] with P_{RF} = -30 dBm.

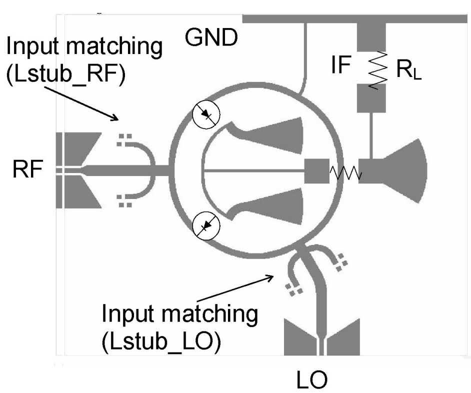

Fig. 2. Mixer layout

The three parameters under investigation for the hybrid optimization, which affect both the circuit and system levels for the mixer, are the LO input power level P_{LO} (system level), the length of the input stub *Lstub_LO* (circuit level) and the load resistance R_L (circuit level).

First, the simulator has been validated with microwave measurements. The picture of the measured test structure is presented in Fig. 3 and the results for measurements vs. simulations is presented in Fig. 4. The measurements were performed using an Agilent 8510 Network Analyzer, a 83650A Signal Generator and a 8565E Spectrum Analyzer. The two measurements are taken for f_{RF} = 24.153 GHz and 24.151 GHz. The RF power level was P_{RF} = -30dBm, f_{LO} = 24.15 GHz and the load resistance used for the measurements was R_L = 20 Ω. Therefore, measurements and simulations agree better for the low value of R_L but it can be seen that the conversion loss improves with higher R_L. Also, there is more agreement for higher levels of P_{LO} because the simulator converges better for values of P_{LO} close to 0 dBm or more.

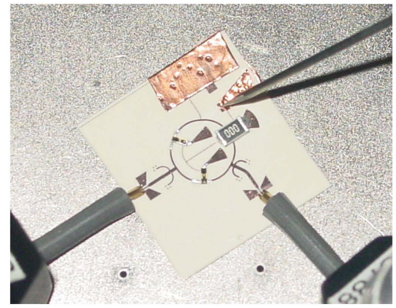

Fig. 3. Fabricated mixer

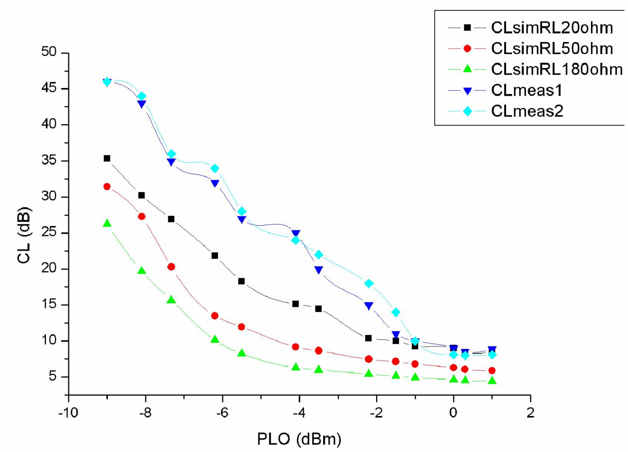

Fig. 4. Measurements vs. simulation

The design space for the two parameters has been chosen such that it represents physically realizable values and incorporates fabrication limitations and design rules. The ranges for the three input variables are presented in TABLE I.

TABLE I.
RANGES FOR THE INPUT VARIABLES

Variable	Low value "-"	High value "+"	Center point
L_{stub_LO} (mm)	0.14	0.3	0.22
P_{LO} (mW)	1	2.5	1.75
R_L (Ω)	75	250	162.5

The responses for the statistical models are the conversion loss *CL* and the isolation between RF and LO *iso_RF_LO*.

The methodology used in the optimization of the mixer structure is presented as a flowchart in Fig. 5. First, DOE is performed to develop the first order statistical model, including all circuit and system level parameters. Then, the model is checked for ultimate lack of fit, that is, if curvature might be present in the output response. If curvature in the response is detected, the analysis is extended to additional axial points indicated by the RSM method, which can account for curvature through second-order model development. Usually, these second-order models are reasonable approximations of the true functional relationship over relatively small regions. Once validated using statistical diagnostic tools, the models approximate the actual system within the defined design space.

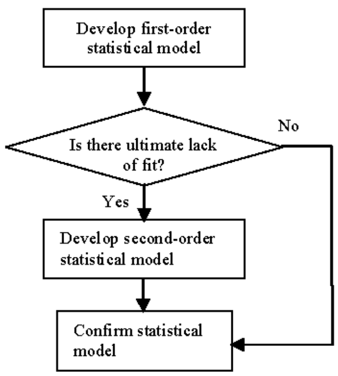

Fig. 5. Procedure for statistical model development

The experimentation method chosen for the first-order statistical model is a full factorial DOE with center points [6]. The factorial designs are used in experiments involving several factors where the goal is the study of the joint effects of the factors on a response and the elimination of the least important ones from further optimization iterations. The 2^k factorial design is the simplest one, with k factors at 2 levels each. It provides the smallest number of runs for studying k factors and is widely used in factor screening experiments [6]. Center points are defined at the center of the design space, as indicated in TABLE I, and increase the capability of investigating the validity of the model, including curvature in the response, and account for variations in the fabrication process of the structure. Since the statistical models are based on deterministic simulations, the variations of the center points were statistically simulated based on a $\pm 1\%$ tolerance for L_{stub_LO}, a $\pm 1\%$ tolerance for P_{LO}, a $\pm 5\%$ tolerance for R_L, and a 3σ fabrication process. Specifically, center points were randomly generated assuming a mean equal to the exact center point value and a standard deviation equal to 0.0007333 mm for L_{stub_LO}, 0.003333 mW for P_{LO} and 2.708333 Ω for R_L.

In this case, a 2^3 full factorial DOE was performed for the first-order statistical model and RSM was needed for the second-order statistical model. Once the models were validated for the model assumptions, the final statistical models were confirmed for prediction of the output variables and an optimization of the tested mixer performed.

III. Statistical Analysis

From the DOE, first-order statistical models were developed, which showed to have poor fit, which means additional simulations have to be performed in order to develop an accurate second-order model. Upon inspection of the statistical diagnostic tools used to validate assumptions of normality and equal variance, curvature was detected for both C_L and *iso_RF_LO*.

The following step was a second-order model development using RSM to attempt modeling the detected curvature in the figures of merit. The statistical models for *CL* and *iso_RF_LO* were both statistically significant at the 95% confidence level. Only R_L was significant for the *CL* and only P_{LO} and R_L for the *iso_RF_LO* model, and the curvature in the model has been alleviated by the R_L^2 term for both figures of merit. The insignificance of L_{stub_LO} is due to the very small interval needed for this application. The models are given by (1)-(2).

$$C_L(dB) = 4.47 - 0.66\left(\frac{R_L - 162.5}{87.5}\right) + 0.8\left(\frac{R_L - 162.5}{87.5}\right)^2 \quad (1)$$

$$iso\_RF\_LO(dB) = -21.06 - 2.62\left(\frac{P_{LO} - 1.75}{0.75}\right) + 2.77\left(\frac{R_L - 162.5}{87.5}\right) - 1.06\left(\frac{R_L - 162.5}{87.5}\right)^2 \quad (2)$$

The models give the possibility to optimize the mixer performance with respect to either figure of merit or both simultaneously allocating any weight factors to each one of them.

Before proceeding to the optimization, the models had to be confirmed. The confirmations of the models were performed for the following arbitrary combination of parameters: L_{stub_LO} = 0.254 mm, P_{LO} = 1.42 mW, R_L = 215 Ω. This configuration was simulated in the circuit simulator and was also predicted with the developed models (1)-(2). The results of the simulation, compared to the RSM 95% confidence intervals defined by the lower and upper bounds for the predicted *CL* and *iso_RF_LO* are shown in TABLE II. Because the simulation values fall into the 95% confidence intervals from the RSM, the RSM models were confirmed and (1)-(2) were accepted as the final models for optimization.

TABLE II.
CL AND *iso_RF_LO* FROM SIMULATION COMPARED TO THE RSM 95% CONFIDENCE INTERVALS

	CL (dB)	*iso_RF_LO (dB)*
Simulation	4.5	-19.702
RSM lower bound	3.46	-19.84
RSM upper bound	5.26	-17.4

IV. Mixer Optimization

The final step in our study was the actual optimization of the benchmarking structure. The optimization goals chosen in this case were a minimum *CL* (weight = 0.75) and minimum isolation *iso_RF_LO* (weight = 0.25). The surfaces for the two figures of merit as a function of the optimizing parameters are presented in Fig. 6, clearly indicating the curvature in the models. The optimization is done based on the plot in Fig. 7. The values that satisfied the two optimization conditions within the ranges presented in TABLE I were P_{LO} = 2.5 mW and R_L = 168.7 Ω, leading to the optimized values of the two figures of merit of CL = 4.42 dB and *iso_RF_LO* = -23.5 dB. The RSM optimized structure was simulated in the electromagnetic simulator and the values obtained for the output variables are CL = 4.73 dB and *iso_RF_LO* = -23.19 dB. These simulation results are in good agreement to those predicted by the statistical models and represent the best reported conversion loss for this type of mixer in this frequency range. This work can be extended to performance capability modeling based on the developed models, to predict the variablity of the outputs based on the input variations at the beginning of the design process. In this way, this approach could enable the derivation of a-priori intervals for the system-level performance for the mixer/radar around the optimal design values, incorporating the fabrication tolerances and the dielectric constant uncertainties.

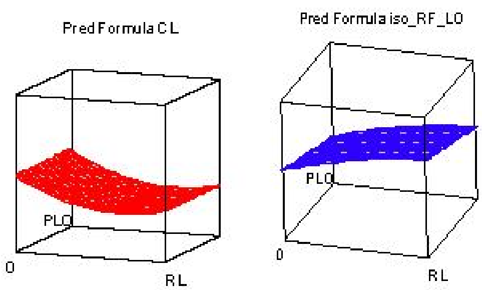

Fig. 6. Surfaces of possible solutions for optimized CL and *iso_RF_LO*

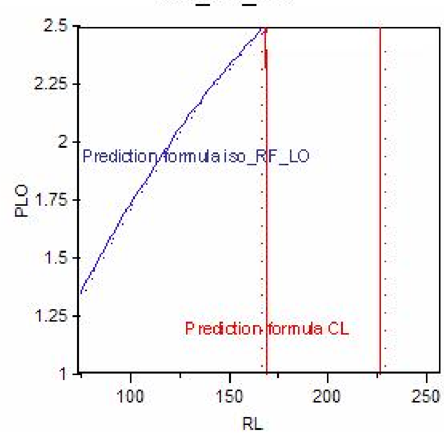

Fig. 7. Intersection of the surfaces representing the possible values of P_{LO} and R_L that satisfy the optimization conditions.

V. Conclusions

The DOE and RSM approaches have been combined with circuit- and system-level electrical simulations to perform, for the first time, the concurrent optimization of the circuit and system level for a down conversion mixer. The experiment was very simple to implement and provided a thorough understanding of the issues to be confronted to in the optimization process. The statistical analysis provided second order design equations including both circuit and system figures of merit, then the optimization was performed simultaneously by allocating arbitrary weight factors to each one of them. The result is the best reported conversion loss for this type of mixer, with a very good isolation between RF and LO ports. Specifically , the proposed optimized 24 GHz mixer shows a 4.5 dB conversion loss with a 23 dB isolation between the RF and LO ports at the operating input power levels. This mixer is part of a low cost, high performance Doppler radar sensor, to be built in an organic technology, with cost-driven design flow, high-performance packaged devices, pick-and-place automated assembly and state-of-the art design for each component of the building block.

Acknowledgement

The authors wish to acknowledge the NSF CAREER ECS-9984761, the NSF ECS-0313951, the Georgia Electronic Design Center (GEDC), as well as the Department of Information and Electrical Engineering at University of Perugia. Special thanks to Federico Alimenti and Luca Roselli at University of Perugia for help with the mixer design.

References

[1] L. Roselli, F. Alimenti, M. Comez, V. Palazzari, F. Placentino, N. Porzi, A. Scarponi, "A cost driven 24GHz Doppler radar sensor development for automotive applications", *Proc. Of the 2005 European Microwave Conference*, 4-6 Oct. 2005.

[2]B. Edde "RADAR: principles, technology and applications," Prentice Hall, Englewood Cliffs (USA), 1993 , pp. 492-494.

[3] S. A. Maas, "Microwave Mixers", Artech House, 1986.

[4] N.Bushyager, D.Staiculescu, L.Martin, J.-H.Lee, N.Vasiloglou and M.M.Tentzeris, "Design and Optimization of 3D RF Modules, Microsystems and Packages Using Electromagnetic and Statistical Tools", *Proc. of the 2004 IEEE-ECTC Symposium*, pp.1412-1415, June 2004.

[5] "Low Cost Mixer for the 10.7 to 12.8 GHz Direct Broadcast Satellite Market", Agilent Technologies Application Note 1136.

[6] J. Neter *et al*, "Applied Linear Statistical Models", 4th Ed., The McGraw-Hill Companies, Chicago, 1996.