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# Concurrent dual-band SiGe HBT power amplifier for Wireless applications

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*This paper presents an investigation of a concurrent low-cost dual-band power amplifier (PA) fabricated in SiGe technology, able to simultaneously operate at two frequencies of 2.45 and 3.5-GHz, including an evaluation of its system level performance potentiality. Taking into account the technology novelty and the lack of device characterization and modeling, a hybrid (MIC) approach has been adopted both for a fast prototyping of the PA and for the evaluation of the device potentiality based on an extensive linear and nonlinear characterization. The comparison of PA performance in single-band or concurrent mode operation will be presented. In particular, the measured PA prototype shows an output power of 17.2 and 17-dBm at a 1-dB compression point, at 2.45 and 3.5-GHz, respectively, for CW single-mode operation, with a power added efficiency around 20%. System-level analysis predicts that, when the PA is operated under the 20-MHz Orthogonal Frequency-Division Multiplexing (OFDM) concurrent signals, the maximum output power levels to maintain the Error Vector Magnitude (EVM) within 5% are 11 and 3.5-dBm at 2.45 and 3.5-GHz, respectively. Moreover, new concepts and possible new system architectures for the development of the next generation of the multi-band transceiver front-end will be provided with an extensive system-level evaluation of the amplifier.*

**Keywords:** HBT, SiGe, Dual band, System analysis, Concurrent mode operation

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## I. INTRODUCTION

Wireless technology has been evolving from cellular to wireless broadband and to personal area network applications. As can be already seen in today's 3G voice/data Systems, users may be moving while simultaneously operating in multimedia streaming sessions or in a broadband data access [1]. To interact with a multi-services network, radio technology should change between an operative band to another and adapting its features according to the different available standards. To this aim, multi-band radio technologies have been extensively addressed by several research projects and covered by the scientific literature [2]. Despite these efforts, presently there is no optimum multi-band radio topology. Basic system-level solutions are referred to as a software-defined radio (SDR), a radio communication system that uses software for the reconfiguration of the digital or analogue part of the sub-system for the modulation and demodulation of the radio signals [3]. Most of the systems in the market still support only a very limited number of standards (e.g. Global System for Mobile Communications (GSM), Universal Mobile Telecommunications System (UMTS) and, when available, Bluetooth). Further communication standards are supposed to enter the market in the near future, and, if possible, they can be used without hardware modifications. The RF transmitter power amplifier (PA) will be a key point of this chain. Today, dedicated PAs achieve very good power added efficiency (PAE) and, as a consequence, long battery lifetime. Any reconfigurable PA, needed for the support of different, not always predefined, communication systems, must compete with these dedicated solutions. Flexible receivers for either multi-band or SDR have been investigated in this field and this paper deals with the evaluation of a low-cost new PA design methodology to be considered as an enabling sub-system for the above-described scenario.

The paper is organized as follows: An overview of the state-of-the-art multi-band PA architectures will be given in Section II, highlighting the advantages and weaknesses for each topology. The PA prototype design methodology and its experimental characterization are described in Section III, while the PA system-level analysis is reported in Section IV. Conclusions are finally drawn in Section V.

## II. MULTI-BAND PA ARCHITECTURES

Multi-band PA strategies can be roughly divided into three main approaches (see Figs 1–3). The most straightforward solution is to use two dedicated PAs coupled by a diplexer, designed to separate the two spectra according to the required communication standards (Fig. 1). The PAs operate at their respective carrier frequencies. The isolation is assured by a diplexer, which could represent a critical issue in case of closer operative spectrum bands. The loss introduced by this diplexer typically is in the range of a few dBs, thus

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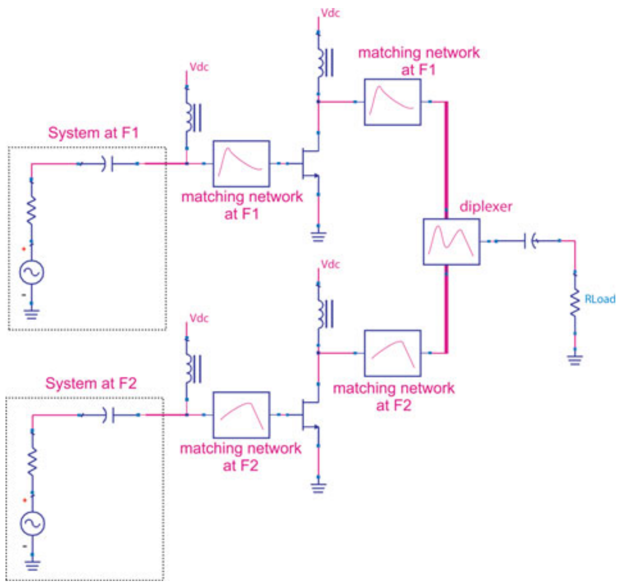

**Fig. 1.** Schematic of combined PAs.

determining a reduction of the resulting overall system performance, in particular at the output stage. For quick product development this solution appears very interesting, but it represents a not optimized solution in terms of costs and performance. A second approach (see Fig. 2) consists in employing tunable/switching components in the matching networks, to enable the capability coping with more than one standard. In this solution, usually referred to as adaptive PA, the efficiency is also enhanced (see e.g. [4]), selecting the proper termination for each power level. The main drawback of this solution, in principle very flexible and suitable for the implementation of software-based controlled subsystems, is related to the losses exhibited by tunable components such as the needed variable capacitors or tunable inductors, affecting the overall system features. Another critical point is represented by the solid-state devices normally included in the matching networks to enable parameter tuning, which introduce linearity constraints. The third approach consists in the so-called concurrent PA, or, in other words, in a system able to simultaneously operate in different bands (Fig. 3). In this case the matching networks are designed to maximize device performances, allowing simultaneous operability in all bands, while avoiding the use of switches or reconfigurable elements and pertinent control voltages (see e.g. [5]). In this case, the most critical point is clearly represented by the matching networks constraints since they have to be able to synthesize the device optimum loads at different frequencies. The aim of this paper is to study, investigate, and evaluate the feasibility of a dual-band power amplifier using low-cost HBT SiGe technology. For this purpose, the concurrent approach (Fig. 3) has been selected since it is the only one that allows simultaneous interoperability in the selected working bands.

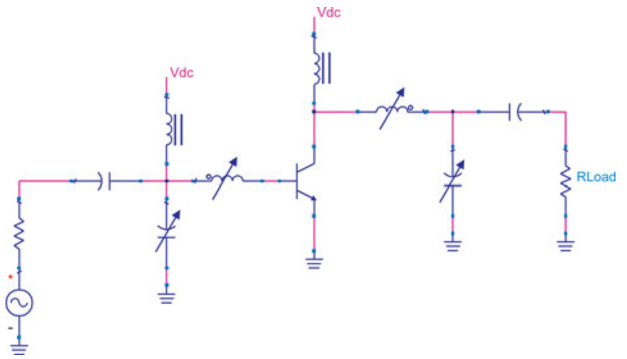

**Fig. 2.** Schematic of adaptive PA.

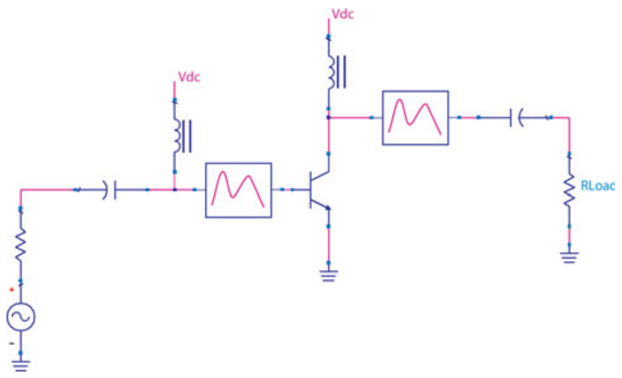

**Fig. 3.** Schematic of the dual-band PA.

## III. PA DESIGN

In order to investigate the features of a concurrent topology, a PA has been developed based on a new SiGe BiCMOS active device, provided by the IHP foundry [6, 7], to operate at frequencies of 2.45 and 3.5-GHz. Accounting for technology novelty and the lack of device characterization and modeling, a hybrid (MIC) approach was adopted for fast prototyping and in order to evaluate device potentiality also. In particular, the following steps were adopted:

- characterization of the active device under small and large signal conditions;
- design of the matching network;
- integration of the PA prototype and tests.

The prototype developed was realized by designing matching networks on a low-cost plastic substrate (TACONIC CER-10) and connecting such nets to the active device through wafer probes, as schematically depicted in Fig. 4.

### A) Active device characterization

The active device was extensively characterized in both linear and nonlinear regimes. Figure 5 shows an HBT cross section.

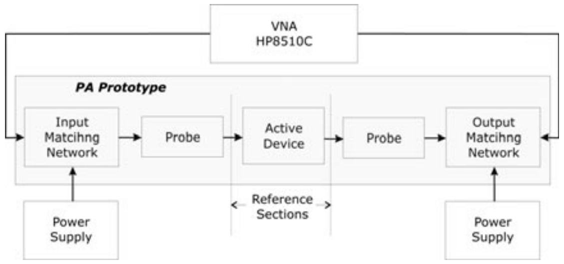

**Fig. 4.** Hybrid (MIC) PA prototype.

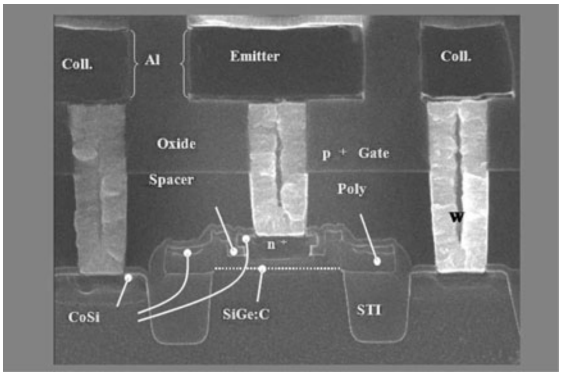

**Fig. 5.** HBT cross section.

Since the DUT is an HBT device, for the static *I*–*V* output characteristics the collector to emitter voltage $V_{CE}$ was varied in the range from 0 to 8.5-V, while the base current $I_B$ was varied from 20-μA to 1.4-mA. The resulting measured *I*–*V* characteristics are reported in Fig. 6. Following that, scattering parameter measurements were performed for different bias points, in the range 100-MHz–40-GHz. Accounting for the DC curve for the design of the PA, the bias point $V_{CE} = 4.5$-V and $I_B = 0.4$-mA was chosen. According to this bias point, Figs 7 and 8 report the corresponding *S*-parameter behavior in terms of input ($S_{11}$) and output ($S_{22}$) reflection coefficient and small signal gain ($S_{21}$), referred to the DUT reference planes highlighted in Fig. 4. Successively, nonlinear characterization was performed for the design frequencies of 2.45 and 3.5-GHz, with an active harmonic load-pull test bench based on the active loop approach [8]. The measured optimum fundamental termination from load-pull maps at 2.45-GHz, at 3-dB of gain compression, was $\Gamma_{L,f_1} = |0.4|e^{j114^\circ}$, showing an output power, and PAE of 19.6-dBm and 39%, respectively (see Fig. 9). The measured DUT input reflection coefficient was $\Gamma_{in,f_1} = |0.83|e^{-j179^\circ}$. For the same bias conditions and compression, at 3.5-GHz the identified optimum load was $\Gamma_{L,f_2} = |0.52|e^{j104^\circ}$, while the DUT input reflection coefficient was $\Gamma_{in,f_2} = |0.91|e - {}^{j177^\circ}$, showing an output power of

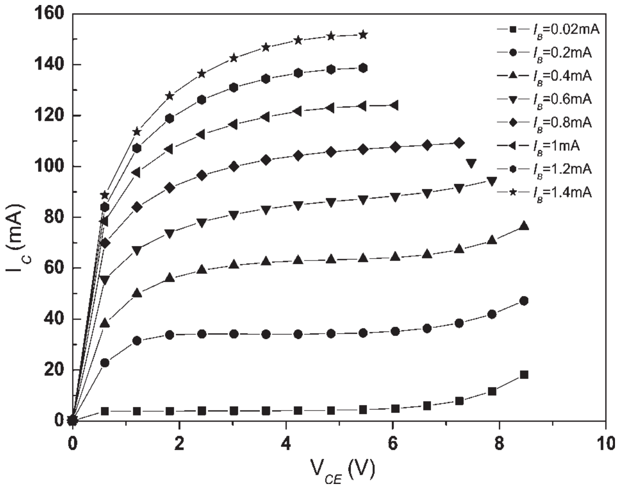

**Fig. 6.** Static device DC characteristics.

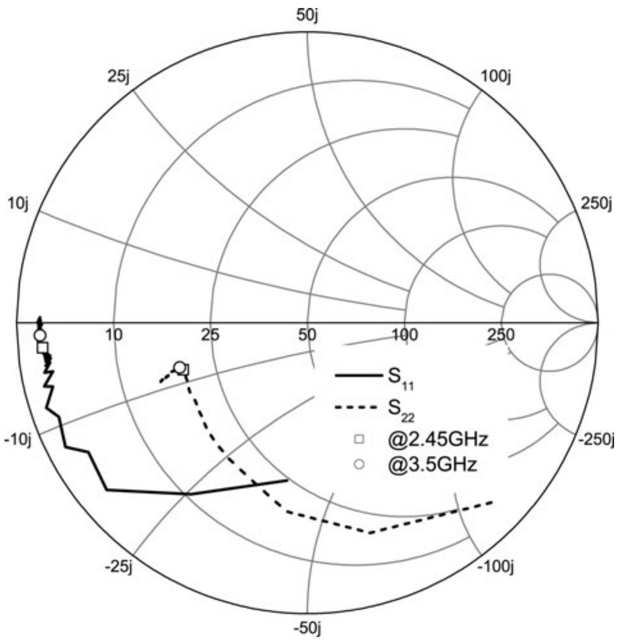

**Fig. 7.** Scattering parameter $S_{11}$ and $S_{22}$ for the DUT in the bias point $V_{CE} = 4.5$-V and $I_B = 0.4$-mA selected for the PA design.

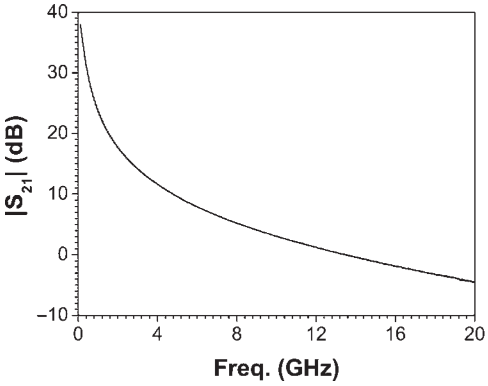

**Fig. 8.** Small signal gain $S_{21}$ for the DUT in the bias point $V_{CE} = 4.5$-V and $I_B = 0.4$-mA selected for the PA design.

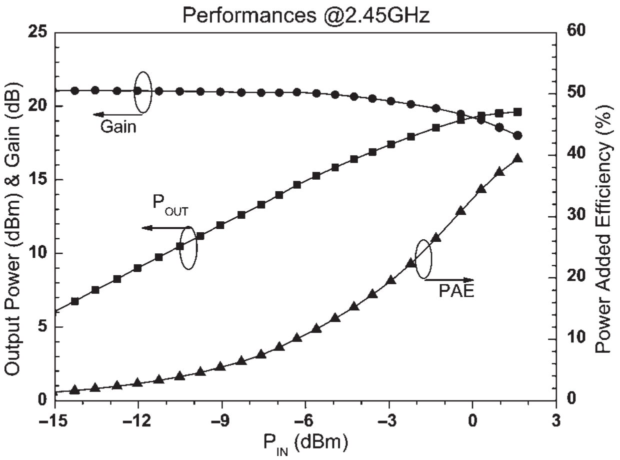

**Fig. 9.** Power sweep on optimum load ($\Gamma_{L,f_1}$) at the fundamental frequency of 2.45-GHz.

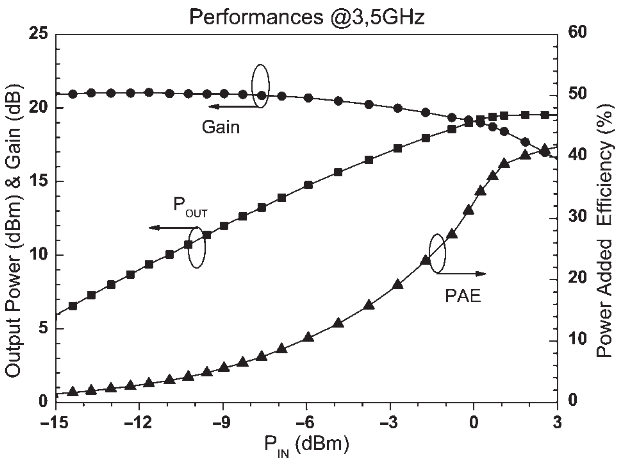

**Fig. 10.** Power sweep on optimum load ($\Gamma_{L,f_2}$) at the fundamental frequency of 3.5-GHz.

19.5-dBm and a PAE of 40% (Fig. 10). As can be noted, the two sets of curves, at 2.45 and 3.5-GHz respectively, exhibit pretty similar figures in terms of output power, PAE, and gain.

## B) PA design

In order to realize the PA prototype, the idea was to design the input and output matching networks to fulfill, across the DUT reference sections (see Fig. 4), the optimum loading condition previously reported. For this purpose, it was required to properly de-embed the contribution of SMAs and probes used to connect the nets to the DUT and the rest of the set-up. The matching networks were designed by using a lumped/distributed approach and following the criteria reported in [9, 10]. The impedance transformation required for the output matching network (OMN) was realized by the scheme shown in Fig. 11, where the impedance transformations realized in each section are also represented. Accounting for the measured *S*-parameter of the output probing connections, the optimum loads $\Gamma_{L,f_1}$ and $\Gamma_{L,f_2}$ to be synthesized in Section A have been de-embedded to obtain the load condition to be fulfilled in Section B. The resulting network transformation from the external 50-Ω termination up to Section B is reported in Fig. 11. A similar procedure was adopted for the design of the input matching network (IMN) to fulfill the conjugate matching conditions represented by the two source reflection coefficients $\Gamma_{s,f_1} = |0.83|\ \exp^{j179^\circ}$ and $\Gamma_{s,f_2} = |0.91|\ \exp^{j177^\circ}$, respectively. The

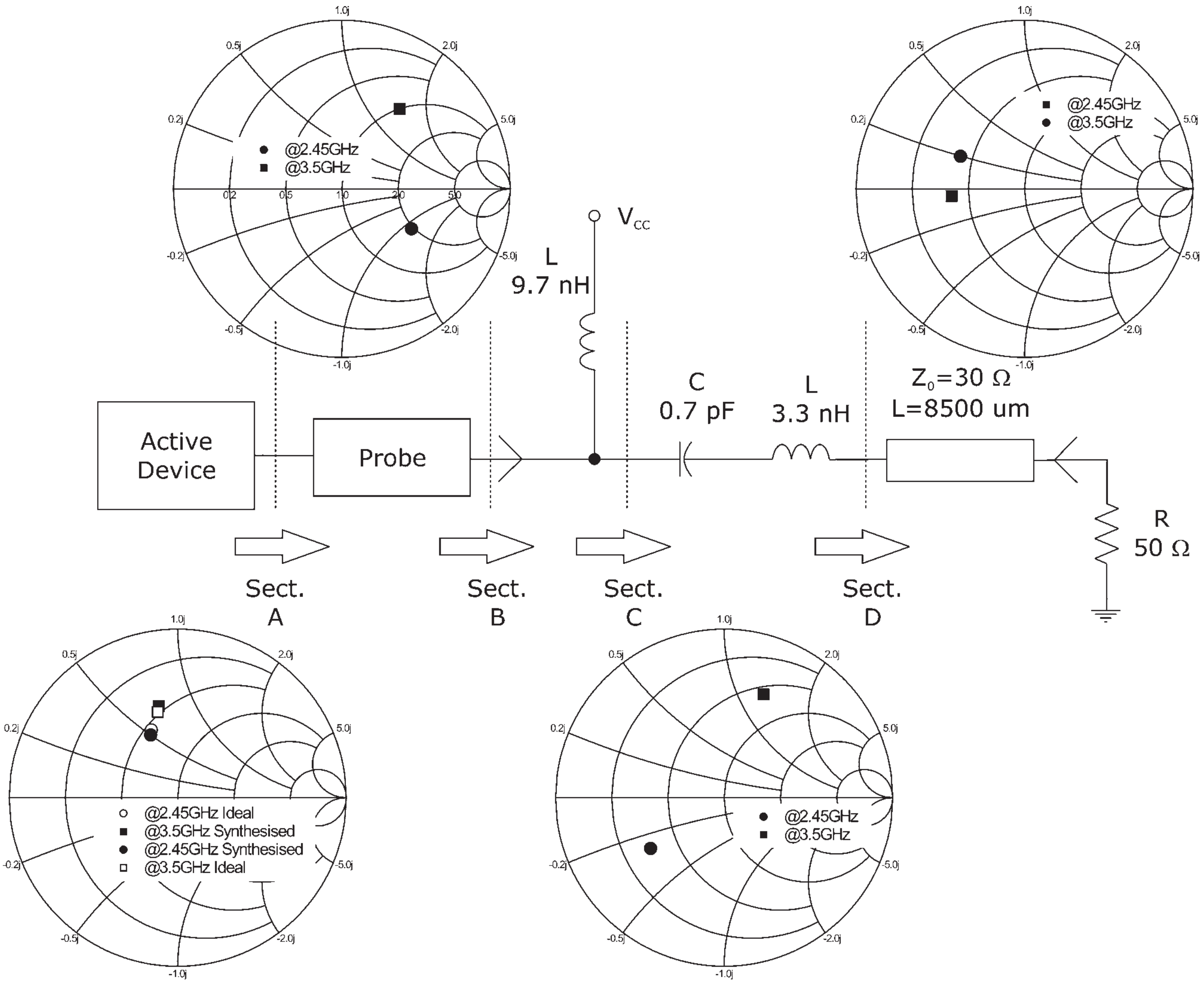

**Fig. 11.** Output matching network.

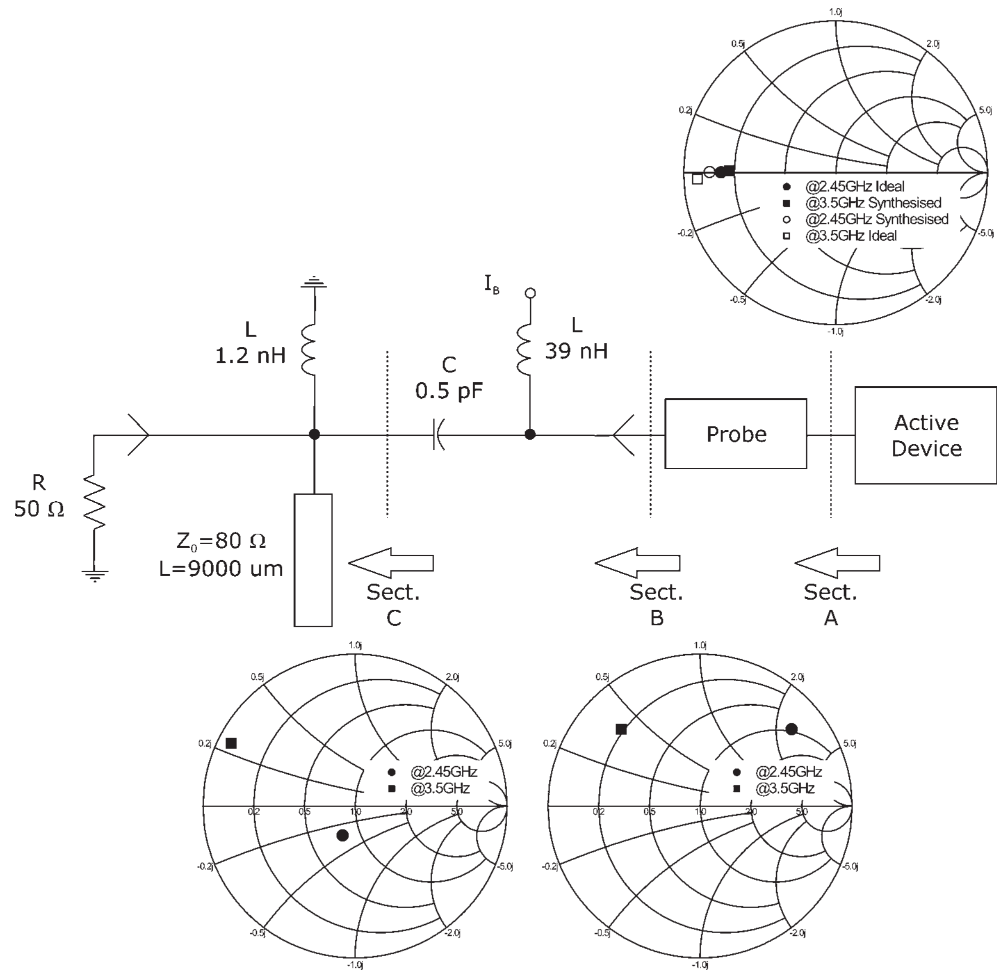

**Fig. 12.** Output matching network.

input network scheme is reported in Fig. 12, together with the loading transformation performed in each section. The pictures of the realized matching networks are reported in Figs 13 and 14, respectively.

## C) PA characterization

In order to experimentally evaluate the performance of the whole test system, the PA was measured both in small signal (SS) scattering parameters and in large signal (CW) power measurements at the two fundamental frequencies of interest. Figure 15 shows the measured transmission $S_{21}$ and matching $S_{11}$ scattering parameter of the amplifier. As expected for this preliminary test structure, the hybrid setup implemented (see Fig. 4) deeply affects the performance of the amplifier, in terms of both absolute gain and actual working frequencies.

For the former, the losses introduced by the matching nets have been estimated to be of the order of 1 and 0.6-dB for IMN and OMN, respectively. For the absolute gain, an actual frequency shift was observed, which was partially compensated through additional delay elements properly tuned during measuremens. Nevertheless, a non-negligible mismatch at the prototype input was experimentally verified, which implies a power gain reduction of the realized PA

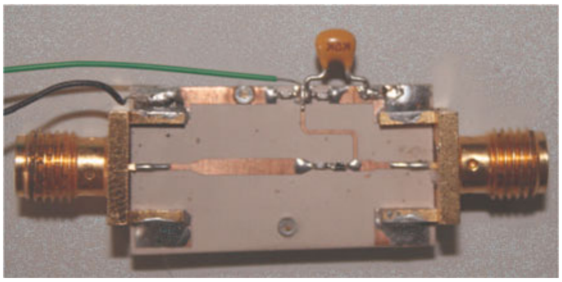

**Fig. 13.** Picture of PA input matching network.

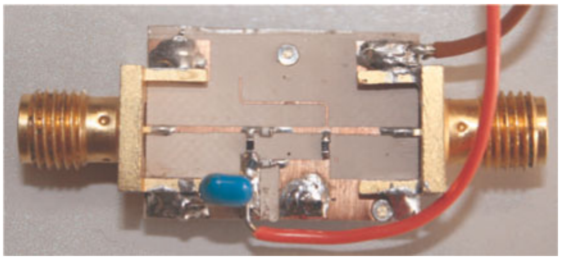

**Fig. 14.** Picture of PA output matching network.

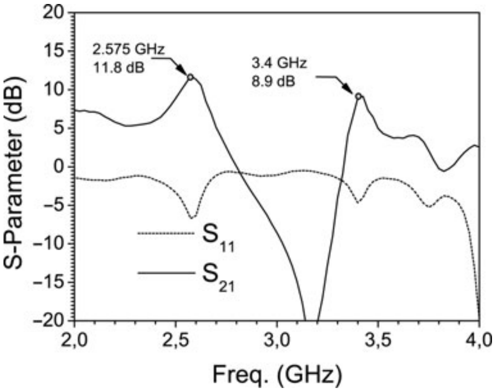

**Fig. 15.** Measured transmission $S_{21}$ and matching $S_{11}$ scattering parameters of the amplifier.

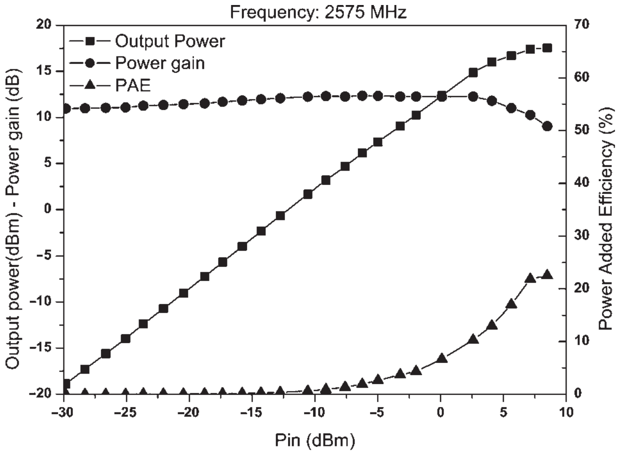

**Fig. 16.** Output power, power gain, and PAE vs. input power ($P_{in}$) at the fundamental frequency of 2.575-GHz.

with respect to the load-pull measurements on the DUT. As a result, the SS gains in the two bands are roughly 12-dB at 2.575-GHz and 9-dB at 3.4-GHz. Figures 16 and 17 show output power, power gain, and power added efficiency (PAE) vs. input power ($P_{\text{in}}$) at 2.575 and 3.4-GHz (maximum of the SS gain), respectively. As can be clearly seen, output power is around 17.5-dBm, gain is near 10-dB, and PAE is close to 20% for both the frequencies. The effect of the setup is also evident from power performance, resulting in roughly 2-dB of output power losses with respect to the stand-alone DUT performance, which could be alleviated in an MMIC realization.

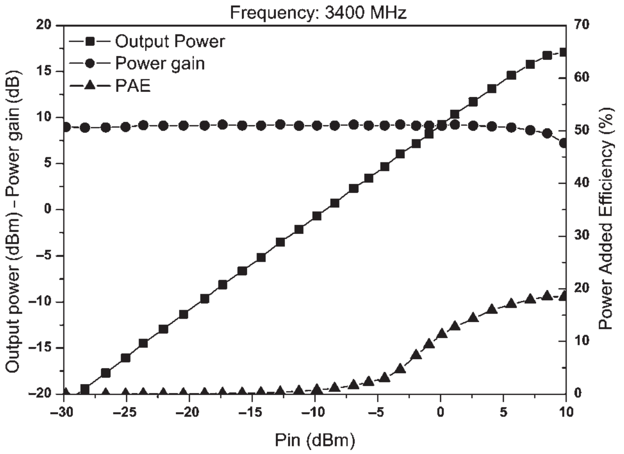

**Fig. 17.** Output power, power gain, and PAE vs. input power ($P_{in}$) at the fundamental frequency of 3.4-GHz.

## IV. SYSTEM-LEVEL ANALYSIS

While the above discussion highlighted the design methodology for dual-band concurrent PA, this section describes its potentiality when implemented in SiGe-MMIC technology and involved in a possible scenario for the next generation of wireless communication. For this purpose, a complete schematic of such a PA was designed following the design rule and completed with all the parts required for its full functioning, which are biasing networks input/output matching networks, stabilizing network, and ballast network. In addition, a CAD platform was adopted to simulate PA behavior when dealing with concurrent dual-band modulated signals. The system was implemented in the Agilent-ADS suite by using behavioral models for the mixers and signal sources, while the two base-band signals were implemented by using the physical layer defined for the OFDM-IEEE 802.16e signal and specifically the 20-MHz bandwidth, 64 QAM mode. A dual-band concurrent transmitter architecture based on the double-image rejection scheme was implemented. This solution, in addition to effective image suppression, enables the capability to simultaneously up-convert two baseband signals around the desired carrier frequencies. The system was co-simulated using the data-flow and envelope engines. The complete design in IC technology has led to a dual-band PA frequency behavior with power gains at two frequency bands of 2.45 and 3.4-GHz which differ from those reported in Figs 9 and 10. This is mainly due to the additional element considered in the circuit, which determines increased losses, and overall a low-pass behavior, which makes the higher operative frequency much more affected than the lower. As a consequence, a larger difference is observed between the two operative frequencies than in the previous discussed experimental results. The system-level analysis firstly considers the effects of the in-band and the out-of-band distortion of a two-tone excitation. An envelope analysis is required to investigate spectral re-growth and modulation integrity, although a significant effect is due to cross-modulation between the two envelopes. To take into account this higher order of complexity, the numerical resources required increase considerably when compared to single carrier–single enveloped analysis. Figure 18 provides a comparison between the response at fundamental for the concurrent dual-band PA when driven by a single-tone and by a two-tone signal. Three simulations have been carried out, the first considering the single-tone excitation at 2.45-GHz, the second considering the single-tone excitation at 3.5-GHz, and, finally, the third considering the simultaneously two-tone excitation; the power level ranges have been kept constant through the simulations. From Fig. 18 it is possible to observe that for the low-level injection the two sets of curves converge to the small signal, while on increasing the power of the single-tone excitation, the corresponding responses exhibit an input referred to 1-dB compression of −5 and 0-dBm at 2.45 and 3.5-GHz, respectively. The higher value of compression for the higher

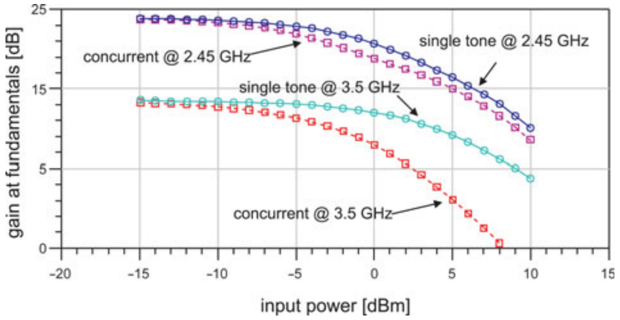

**Fig. 18.** Gain comparison of the large-signal single-tone and two-tone analyses of the concurrent dual-band PA.

band is mainly due to the reduced gain exhibited by the PA at this frequency. When considering the concurrent excitation, the input power level at which the gain decreases by 1-dB reduces sensibly with respect to the single-mode operation. In particular, we observed a reduction of approximately 3-dB for the lower band and 7-dB for the higher band, due to the different gain figures exhibited by the PA, causing a change in the dynamic load lines, in a way very similar to typical mixer operation. The power levels for the two digitally modulated signals were fixed in order to hold, in the concurrent dual-band operative conditions, the maximum EVM within 5%. These values result in output power levels of 11 and 3.5-dBm, respectively, at 2.45 and 3.5-GHz. That value of EVM is typical for system communication requirements involving OFDM broadband signals, e.g. WLAN or WiMAX. The analysis results of the EVM in the three different operative conditions are reported in Table 1 for 11 and 3.5-dBm, respectively, for lower and higher frequency. In the table, System # 1 refers to the modulated signal with center band at 2.45-GHz and System # 2 to the one at 3.5-GHz. As can be noted from the table, System # 1 does not improve its figure sensibly, while System # 2 exhibits a significant reduction of the EVM from 5.2 to 1.2%, moving from the concurrent to the single-band operation mode. A different point of view of these results is achieved observing the spectra for concurrent and single-system operations. With reference to Figs 19 and 20, it is possible to clearly observe modification of the PA output spectrum in the two bands and for the two different operations. While the integrated power for the two systems does not change considerably, moving from single systems to concurrent systems, the gain flatness and the out-of-band spectrum change significantly only for the 3.5-GHz system. This is a result consistent with the EVM figures reported in Table 1 and with the compression characteristic reported in Fig. 18, providing better insight into the operation of the dual-band PA.

**Table 1.** EVM calculation for the dual-band PA.

| | **EVM Sys # 1 ON Sys # 2 OFF** | **EVM Sys # 1 OFF Sys # 2 ON** | **EVM Sys # 1 ON Sys # 2 ON** |
|---|---|---|---|
| Sys # 1 | 4.8% | n. a. | 4.9% |
| Sys # 2 | n. a. | 1.2% | 5.2% |

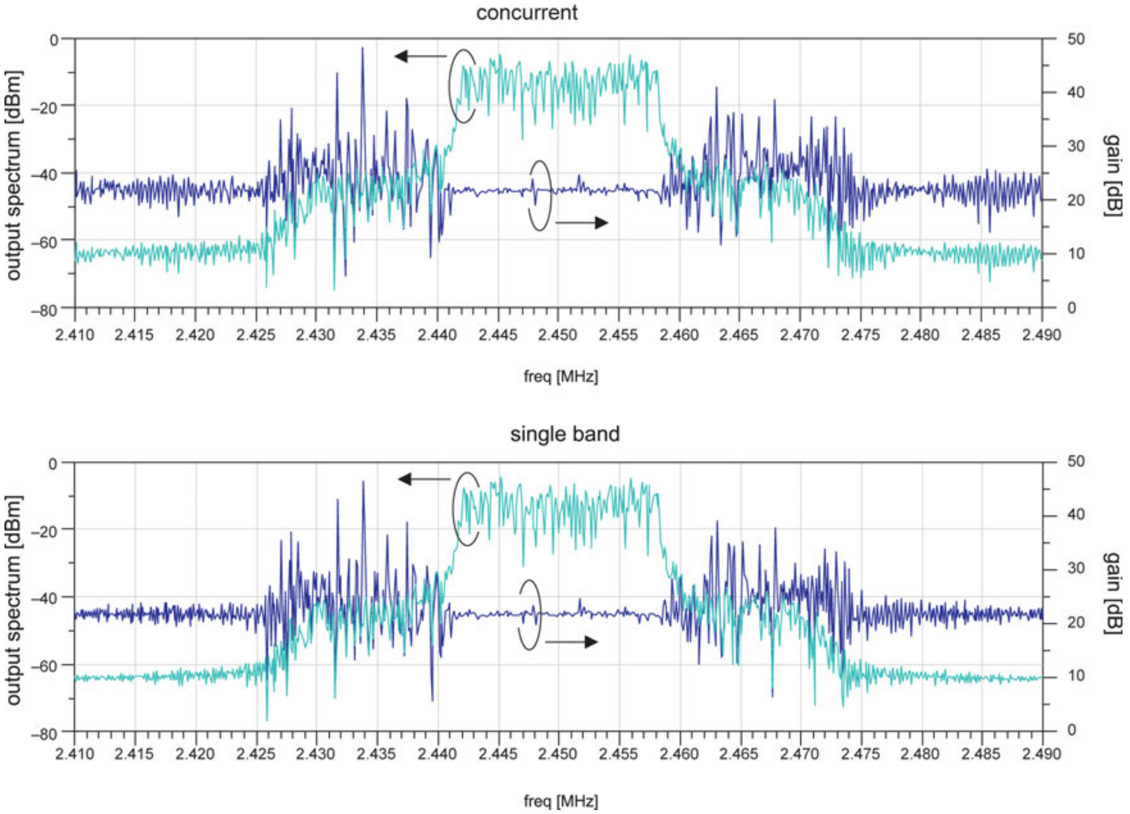

**Fig. 19.** Comparison between spectra at 2.45-GHz in single-system operation (bottom figure) and in the presence of a concurrent system at 3.5-GHz (top figure). The graphs also report the large signal gain of the PA.

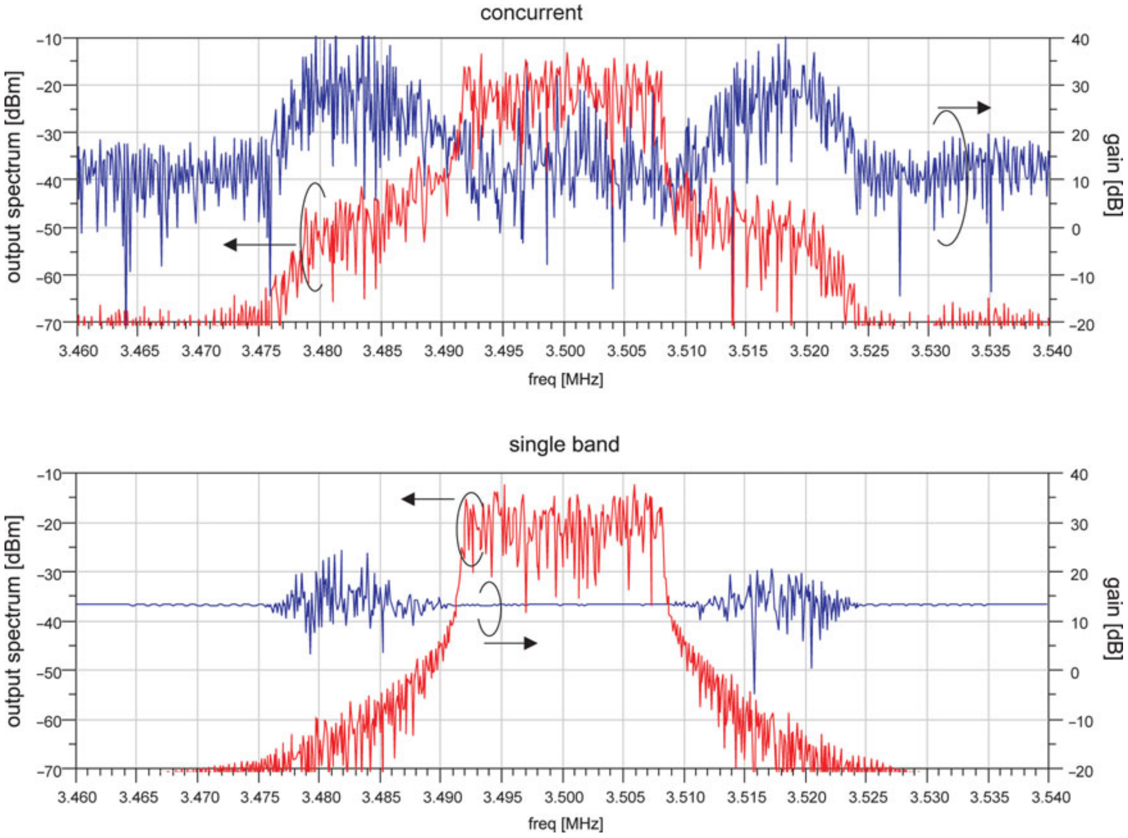

**Fig. 20.** Comparison between spectra at 3.5-GHz in the single-system operation (bottom figure) and in the presence of a concurrent system at 2.45-GHz (top figure). The graphs also report the large signal gain of the PA.

## V. CONCLUSIONS

This paper has dealt with the design of a concurrent low-cost dual-band PA fabricated in SiGe technology and its system-level investigation. A hybrid MIC approach has been adopted both for a fast prototyping of the PA and for the evaluation of the device potentiality based on an extensive linear and nonlinear characterization. This has permitted the design of matching networks in order to optimize their behavior at 2.45 and 3.5-GHz. The measured PA prototype has shown output powers of 17.2 and 17-dBm at a 1-dB compression point, at 2.45 and 3.5-GHz, respectively, for CW single-mode operation, with a PAE around 20%. Nevertheless, the dual-band PA design methodology presented here and its investigation at system level highlighted new concepts and possible system architecture solutions for the development of the next generation of a multi-band transceiver front-end.

## ACKNOWLEDGEMENTS

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