CHAPTER 7 CONCLUSIONS AND IMPLICATIONS

7.1 INTRODUCTION

Chapter 1 and Chapter 2 dealt with the initial research question and hypothesis and a comprehensive literature review in order to establish a foundation for its answer. The research question dealt with looking for a method that can be employed to speed up the design on PAs and their passives for a range of wireless applications while retaining the high quality of amplification. Chapter 3 focused on the methodology of the research procedure and specified the process essentials and tools that were used. Chapter 4 highlighted design routine that lead to Chapter 5, which documented the simulation results supporting the research hypothesis. The layouts of two PAs submitted for fabrication as well as measurement results and their analyses were described in Chapter 6.

The goal of this chapter is to make critical evaluation conclusion of all the research and data gathered in this thesis, and summarize this in a final, concluding section that emphasizes the theories and hypothesis. This is backed up with suggestions for future research on this topic.

7.2 CONCLUSIONS ABOUT THE RESEARCH PROBLEM

In Section 1.2 it was hypothesized that the equations describing the PA and inductor models can be used as a starting point in the development of a set of algorithms which should allow the best possible PA to be found and designed for a given set of specifications such as the PA bandwidth, centre frequency and class of operation. It was is also hypothesized that another set of algorithms can be used to determine geometry of a spiral inductor that gives the highest possible Q-factor, using process parameters for a particular process.

The hypothesis was proven by applying a developed routine to successfully synthesize a number of inductors for the AMS S35 process as well as to design a number of switch-mode PAs utilising the same spiral inductors.

The accuracy of the single-π model used for describing the inductor, the main passive component of any PA, has been verified by comparison between the results based on modelling and results based on EM simulations performed in Cadence Virtuoso Spiral Inductor Modeler, allowing the characterisation of a large number of inductor geometries. This also allowed for verification of the developed spiral inductor search algorithm, due to the fact that 3M and TM inductors designed by the inductor search algorithm could now be verified by EM simulations. Experimentally, a number of square planar spiral 3M and TM inductors were identified to have been characterized by the AMS. The comparison was made between the results obtained by calculations based on modelling and experimental results given by AMS; and it was established that the model analyzes the inductance value of inductors with an average relative error of 3.6 %. With Q-factors taken in evaluation, it has been established that average relative errors differ, with error being as low as 3.9 % for 3M inductors and as high as 34 % for TM inductors. The latter discrepancy has been explained by the fact that for inductor structures with less prominent influence of substrate parasitic, the simplistic assumption of the series RL circuit for the spiral itself yields a pessimistic Q-factor estimate.

This research also shows that with the correct design method which includes optimisation for operation at correct frequency, quality factors in excess of 10 can be obtained for square spiral inductors without resorting to any of techniques described in Sections 2.3.1.2, 2.3.1.3 or 2.3.1.5.

Sections 2.2.5.2 and 2.2.5.3, theorize that in high power and low voltage supply applications, antenna resistances reaching values of less than 10 Ω would be needed for an optimum PA performance. This research proved this practical and provided algorithms that automate impedance matching from designed to standard antenna impedances (50 Ω).

The largest contribution of this research was a set of *algorithms for designing the switch-mode PAs*. Simulations were used to determine that for the complete routine-driven PA system design, that includes output matching and utilisation of real (spiral) inductors, the switch-mode power amplifiers for 50 Ω load at 2.4 GHz centre frequency can be designed applying the streamlined method of this research for the power output of about 6 dB less than aimed. This power loss was expected, and it can be attributed to the non-ideal properties of the driving transistor and Q-factor limitations of integrated inductors, all of which was described in detail in the literature review in Chapter 2.

Additional algorithms, such as one for the SPICE netlist extraction and the spiral inductor layout extraction into industry accepted CIF and GDS II formats were found beneficial for the ease of manipulation with designed PAs as well as the inductor structures. This presents a step forward towards designing a compact EDA tool.

The layouts of two full PA configurations (one Class-E and one Class-F) implementing spiral inductors have been fabricated in the IBM 7WL SiGe BiCMOS process for the purpose of obtaining the measured results. Although the first designs were completed in the AMS S35 process, this allowed for confirmation of the theorized fact that while all results presented in this thesis were obtained for a single fabrication process, the principles devised in this research are technology independent and that they can be used with different BiCMOS processes, as long as process parameters are made available before carrying out the design. Naturally, in the BiCMOS process, the active device chosen is an HBT; but the choice of the active device is arbitrary and depends on the application, with the recommendation that wide transistor structures should be used to physically support high currents; meaning that a CMOS process with NMOS as driving transistor can be used should the need arise (for an example of a CMOS implementation related to this thesis please see [107]). Upon fabrication, the aspects that cannot be covered in simulations, such as the influence of parasitics, have been investigated. It was established that, at least in the case of Class-E amplifier, they corresponded well with the simulations that included packaging parasitics.

All algorithms presented in this research were devised in MATLAB. Flow diagrams of all design algorithms were presented in Chapter 4, while the complete listings of the MATLAB routines utilising them are given in Appendix A.

7.3 IMPLICATIONS FOR THE THEORY

This research leaves two major implications to the existing theory.

- In Chapter 2 it was seen that although the theory of switch-mode PAs is well developed, streamlined approach is generally not employed when designing PAs. Classic design models, some even dating back to 1975 (Sokal), have been interrelated into a set of algorithms that will enable rapid PA design.

- The existing theory involving monolithic spiral inductor design was expanded by means of addition of the spiral inductor design algorithm. Although spiral inductor design algorithms were intended to expand the existing body of knowledge for designing PAs, they implicitly expand the theory of any application that requires integrated inductors, such as LNAs, DC to DC converters or VCOs.

7.4 IMPLICATIONS FOR FUTURE RESEARCH

Suggestions for the improvement and expansion of the concepts derived in this work for future research are given below.

- The method devised in this research analyzes only one type of spiral inductors, viz. square spiral single-layered inductors (with the exception of octagonal inductors briefly tackled in Chapter 6). Various spiral inductor configurations have been researched in Section 2.3.2, and the routine could be expanded to include different spiral inductor options, such as spirals of different geometries (e.g. hexagonal or circular), or tapered or multi-layered spirals.

- In modelling the spiral inductors, it has been assumed that there was no ground plane between the spiral and the substrate. The IBM 7WL process developers offer inductors with two types of ground planes in their standard library [101], which result in two different sets of Q-factors. The modelling of inductors could be expanded to cater for different ground planes available in different processes.

- It was observed that in certain cases, the calculated Q-factor had been underestimated. The inductor design algorithms could be improved by replacing the simple single-π inductor model with one of the more advanced models, all described in Section 2.3.2.3. This, however, would require more input parameters to the routine, and the inductance search algorithm would take longer to converge.

- The method looks into only two types of switch-mode PAs, i.e. Class-E and Class-F. It could be expanded to include inverse classes, such as Class F^{-1}, or hybrid classes, such and Class EF into the list of PA configurations available for the design.

- An attempt could be made to streamline the design of classic (i.e. non switch-mode) PAs.

- The method devised here deals only with output impedance matching. Therefore, in Section 4.6, a cut-and-try method grounded on simulation-based *S*-parameters analysis is proposed in case an input impedance matching is needed to complete the design. The theory could be expanded to devise algorithms for input impedance matching as well, which would make the system design routine more complete.

- As stated earlier in this chapter, although spiral inductor design algorithms were intended for the use with PAs, they could also be used as a starting point for devising algorithms for other devices that make use of inductors, for example for an LNA described in [18]. If such algorithms are combined with the PA algorithms presented in this work, a complete RF amplifier EDA software package could be obtained.

- As stipulated in Chapter 2, as frequency of operation increases beyond about 20 GHz (microwave as opposed to RF frequencies), it becomes possible to utilise transmission lines instead of passive components for the PA design as well as for the matching. The transmission line theory could be researched in order to expand the algorithms of this thesis for the use in millimetre-wave applications [114, 115].