AC 2011-1289: PROJECT-BASED LEARNING EXPERIENCES IN RF AND MICROWAVE WIRELESS COMMUNICATIONS SYSTEM COMPONENTS

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Project-based Learning Experiences in RF and Microwave Wireless Communications System Components

Microwave and Radio Frequency (RF) Engineering is seeing renewed interest by undergraduate students, not only in job opportunities that the wireless area affords, but also with students trying to understand what is 'under the hood' in the ubiquitous wireless devices they often (sometimes too often) use. A veritable alphabet soup of wireless applications (WiFi, WiMAX, RFID and ZigBee to name but a few[a]) are not only in use now but wider bandwidth, faster wireless networks are projected for the future. In fact, the International Technology Roadmap for Semiconductors (ITRS) shows that RF and "wireless applications may replace computers as the key driver in manufacturing" over the next 10 years[1]. In addition to the challenges in lower power applications, another key component of some wireless systems is the high power output amplifier that drives the antenna and is a major consumer of system (especially battery) power. Indeed, much work continues to be done in industry on high efficiency power amplifiers (PA) since in most portable wireless devices, the PA is often the most power-hungry of all the sub-systems, possibly even more than the digital processors. High efficiency is critical so that as much DC energy is converted to usable RF energy and not wasted in heating up the device.

A number of schools have introduced RF design classes to fill this student interest. From the faculty member's perspective, the increased student interest in the wireless area as described above provides a wonderful opportunity to further enhance student learning and engagement in the area of system engineering, electronics and high frequency design and construction techniques. Some schools have used high frequency design classes from a theoretical perspective but with a lower frequency project component to illustrate the timeless concepts. Other schools[2-4] are using the latest PC-soundcard based software defined radio (SDR) kits and ideas to illustrate receiver concepts as well as I/Q modulation schemes; PC software from external sources are used to process the I/Q signals from the hardware SDR and so there is a fear that some important concepts may be lost through the use of the 'black box' software. However, the hardware component is still invaluable for students to get an understanding of the material. This 'return to hardware basics' approach has been heavily utilized at Villanova University over the last few years with a number of courses and independent student projects that illustrate these receive and transmit principles. This paper will build on a series of past papers in outlining the senior level elective sequence as well as a series of high efficiency power amplifier projects undertaken as independent studies. All of these experiences are suitable for undergraduate students and with some modification, could be useful in graduate level courses.

Undergraduate Curriculum Track

Details on the undergraduate track have been covered in detail in a previous work[5] but will be summarized here for completeness. The overall curriculum track (Figure 1) begins with the required Engineering Electromagnetics course in the junior year. In keeping with the curriculum track concept, an introduction to on-chip passive structures (on-chip resistors, capacitors, inductors and transformers) is introduced during the relevant discussions on the electromagnetic origins of these elements (details of this introduction can be found elsewhere[6]).

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[a] For ease of reading, a listing of these and other abbreviations used in this paper are tabularized in Appendix B.

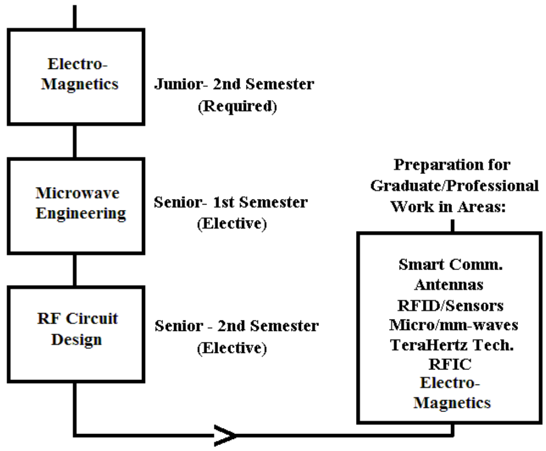

Figure 1. RF and Microwave Engineering
Undergraduate curriculum flow [From [5], © 2007ASEE]

The enrollment in the senior elective sequence shown in Figure 1 varies annually, ranging from as few as 5 or 6 students to as many as 15 to 17 students. The Microwave Engineering course emphasizes passive microwave passive circuit design and utilizes chapters 2-8 and part of Chapter 10 of reference[7]. These topics include

- Transmission Line Theory and Impedance Matching;
- N-port Network Theory;
- Physical Transmission Lines
- Microwave Power Directivity; and
- Microwave and RF System concepts introduction

The Microwave Engineering course includes weekly laboratories where students perform basic microwave measurements using traditional microwave laboratory equipment (slotted lines, SWR meters and waveguide components) and learn to use a contemporary microwave and RF CAD tool (the most recently used CAD software was Ansoft Designer SV). In addition to these weekly reinforcement exercises, the students are assigned a project to use the tools studied throughout the semester to design, simulate, layout and test a prototype microstrip low pass filter circuit based on LC ladder prototype in the nominal 1000 MHz frequency range. The students used CAD for the design and simulation and implement the final prototype using inexpensive 1/16” thick single sided FR-4 printed circuit board. Over the years, students have constructed these commensurate line filters using easily obtainable copper tape (1/4” and ½” is used), cut to width and length using single-sided razor blades (never double-sided razors). More recently, a PCB milling machine has been employed to take direct CAD layouts and put them directly to the FR-4. In both schemes, pass band insertion losses of less than 0.2dB and stop band rejections of greater than 50dB are easily obtained using both techniques. The students then use an HP-8510B Automatic Network Analyzer to measure the S-parameters of their final prototype and compare with the original set of specifications. Figure 2 shows examples of two 3rd order commensurate line filters using both techniques.

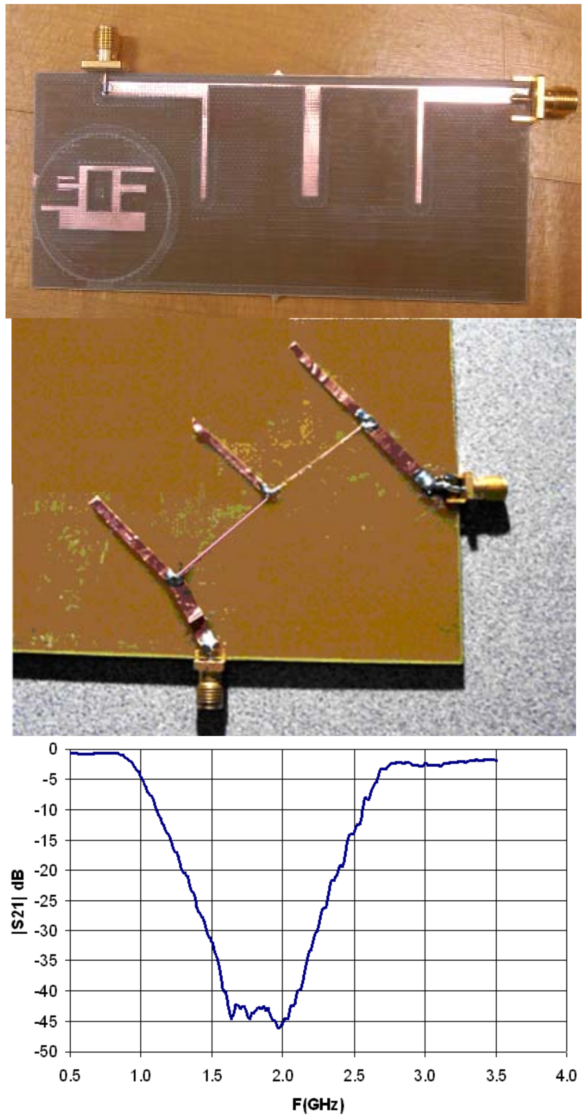

Figure 2: Examples of student-designed nominal 1.0GHz passive microstrip commensurate line low pass filters based on LC ladder prototype circuits: milled (top) and copper tape (bottom) versions. Also shown is the measured performance of the top circuit. [Middle figure from [5], © 2007ASEE]

The RF Circuit Design course is a follow-on course to the Microwave Engineering course and focuses on more active RF and microwave circuits and uses a number of hardware and CAD design projects to reinforce student understanding. In this course, the students design and fabricate and test a high frequency receiver front end and correlate the system design specifications and measurements with the material presented in this course as well as the systems concepts introduced in the previous course. The RF Circuit Design course covers the following high-level list of topics

- Advanced Filtering Concepts;
- Antenna and Signal Control;
- Mixer, Amplifier (low noise and power), and Oscillator Design

- Oscillator Design using primarily reactance-based feedback; and
- Antenna Design with a focus on low profile printed circuit antennas.

As the list of topics above is covered in lecture, an attendant CAD exercise and construction project is assigned as part of the classroom experience. The major course project recently has been the design, simulation and fabrication of a 900 MHz receiver front end that down converts the 900 MHz signal to an intermediate frequency (IF) of approximately 50 MHz. To provide a real life component to this project, a set of beacons transmitters in this frequency range and available in our geographic region is utilized for the classroom[b]. The block diagram for this 900 MHz receiver system is shown in Figure 3. Commercial off the shelf components are used for the LNA and the diode mixer, with microstrip passive circuits used for the input band pass filter (BPF) and branch line coupler. Alternatively, two signal generators, one for LO and one for the RF signal to down-convert may be used in the absence of such on the air resources. Other design possibilities that have been used in this microwave and RF program are to down convert one of the higher digital television channels to lower frequency channel (such as Channel 2 or 3).

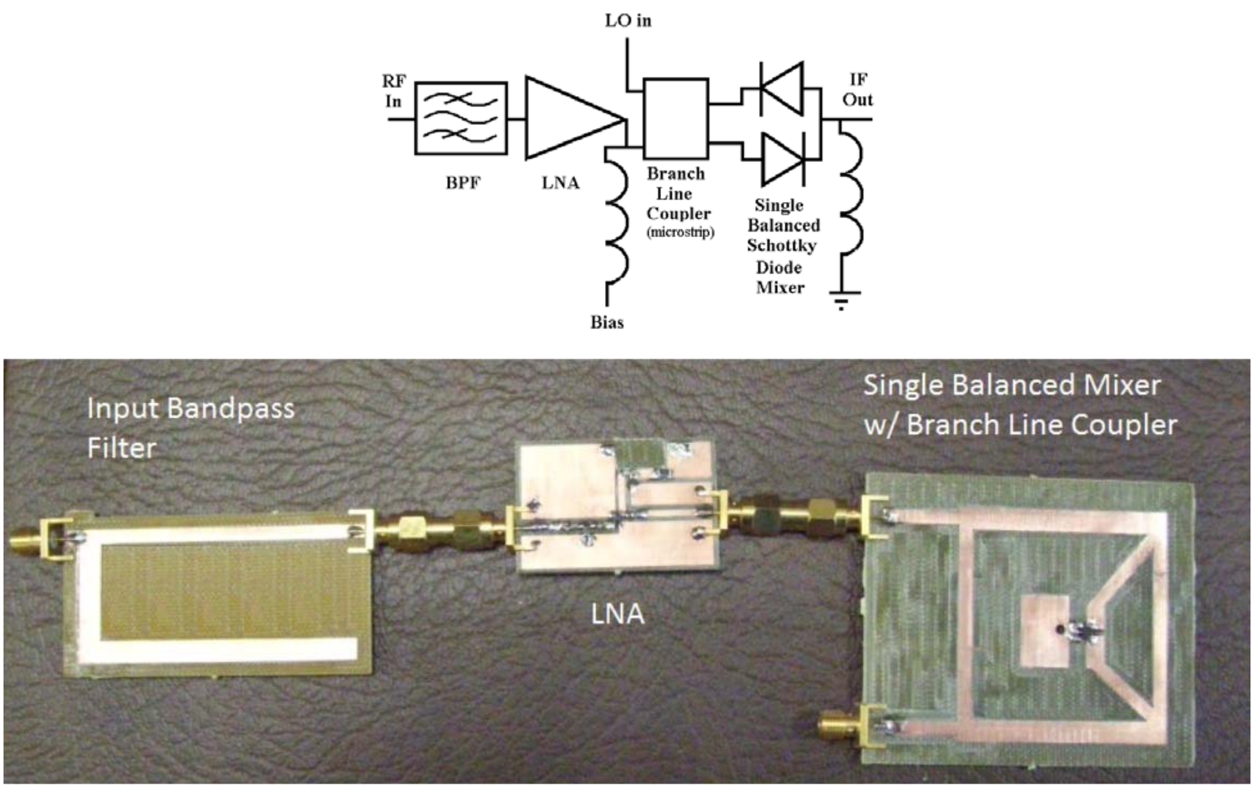

Figure 3. RF front end block diagram and a photograph of the corresponding student-designed circuit [top figure from [5], © 2007ASEE].

[b] This beacon signal is continuously transmitted from W3CCX/B with an easily identified signal of 30 seconds of continuous carrier and 30 seconds of Morse code identification. There are a number of beacons throughout the country that may be found through the amateur radio community to provide this 'real world' project to other schools.

Once the students see the relationship of RF and Microwave Engineering to their wireless consumer devices, they want to explore these concepts even further. Over the last several years, senior students have done a number of high efficiency power amplifier projects. The first PA project utilized a readily available (and quite inexpensive) switching MOSFET, the IRF510 (Figure 4). This project focused on obtaining high efficiency power amplification at 7.0 MHz. In this project, the student not only had to perform a time domain simulation of the amplifier as part of the design, the student also had to construct the required toroid coils for both Class E waveform shaping as well as matching to the required 50 Ohm load termination. This type of project is readily transportable to any university program since the frequency is low and the parts are very inexpensive (the MOSFET is about $1.00 and the toroid forms are less than $1.00). In addition, the low frequency allows simple breadboarding techniques to be used. The amplifier exhibited 69% power added efficiency (PAE) with 8.0W output using a 12.0V power supply.

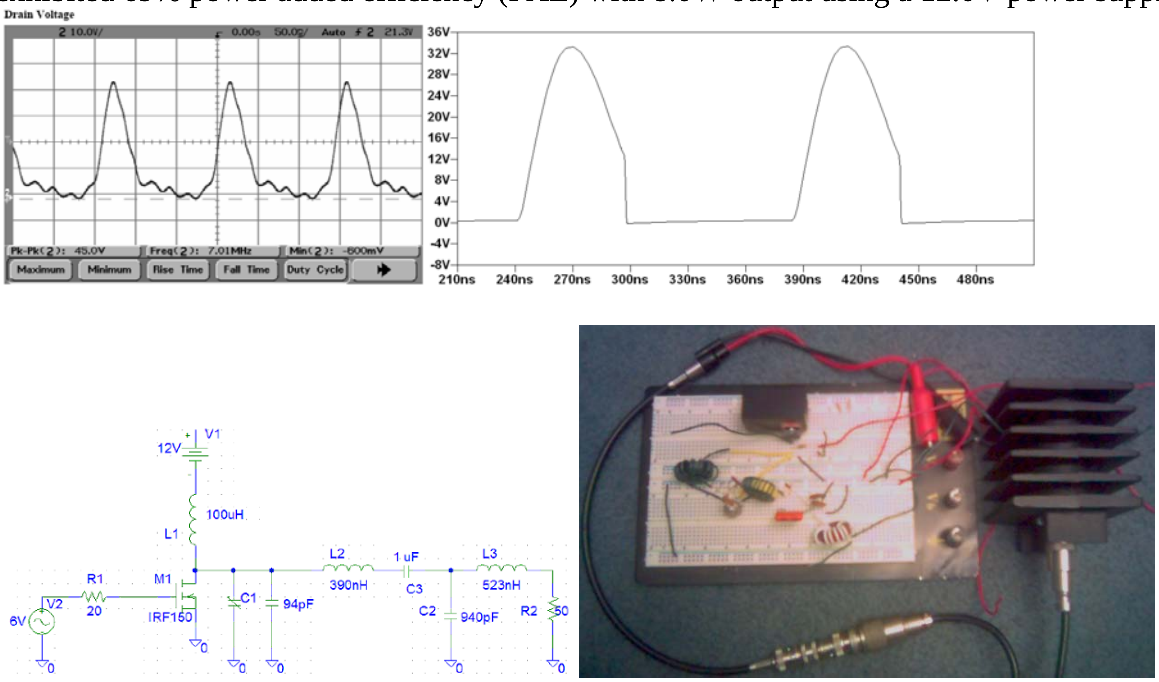

Figure 4. Top: Measured and simulated Class E time waveforms. Bottom: Schematic diagram and fabricated circuit of 7.0 MHz Class E amplifier (the large black object is a 50 Ohm high power load).

Since the initial low frequency PA project was intended to provide a 'higher bar' for the students to reach, these power amplifier projects have been based in the VHF band (primarily 144 MHz) and have concentrated on switching-type amplifiers (Class E and F). All students doing these projects have had the first Microwave Engineering course and are taking the RF Circuit Design course concurrently; these PA projects do not overlap the material in the second course. Using CAD packages such SPICE, the students can gain insight into the impact of waveform engineering[8] and the impact in the time-domain on the interplay between wave shaping networks and the overall amplifier efficiency. Figure 5 shows an example of one such student-designed 144MHz PA. All design work and construction, including board layout (notice the student 'artist' initials in the figure) is done by the students. With a 4.0V power supply, this circuit exhibited a 70.48% PAE (85.1% drain efficiency) with approximately 1.8W of output power into a 50 Ohm load.

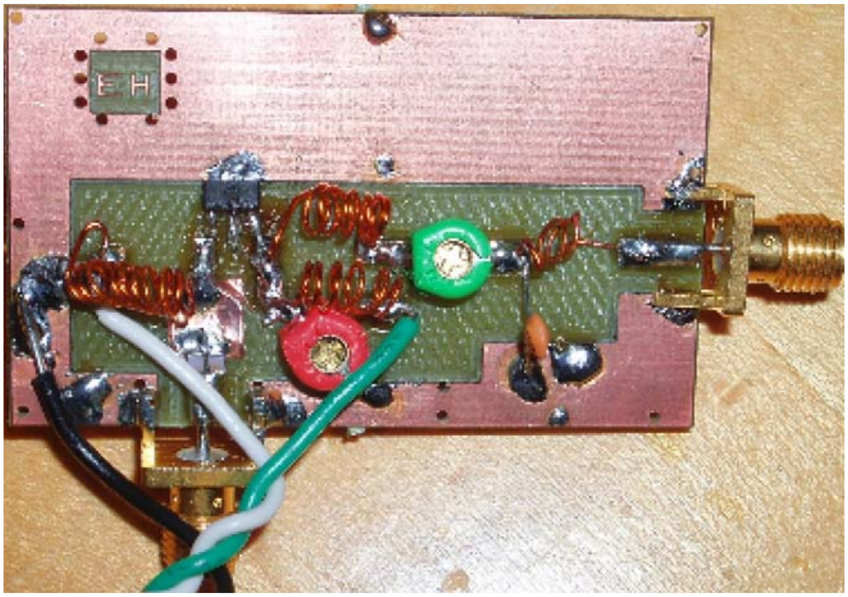

Figure 5. Student designed 144 MHz Class E power amplifier. Notice the 'artist's initials' in the upper left hand corner.

Course and Student Outcome Assessment

Several assessment methods have been used to gauge the level of student outcome achievement in the microwave and RF program. These assessment tools have evolved from being able to achieve the design goals in various course-related projects to more summative assessments using reflective assessments at various times during the course. These more quantitative assessments will be described here.

For the first course in microwave networks, students were presented a reflective questionnaire at the completion of the course to gauge their level of skills enhancement in a number of technical areas associated with the first course in primarily passive network. The technical areas are shown in Appendix A under the 'Microwave Networks' heading with the results of the assessment shown in Figure 6 (red bars). As shown in the figure, the students noted significant enhancement of technical skills in the material covered in this course; these results correlated well with student performance in the course as well. The evidence of skills enhancement related to Questions 1, 3, 5, 6, and 7 was further supported by the results of the final course project (described earlier with an example shown in Figure 2). The skills reinforced by the final project are practical transmission lines, use of the Smith chart, lumped and distrubuted filter design and the ability to complete the design-fabricate-test loop for the filter. The assessement also indicated, however, a somewhat lower level of comfort in understanding of system issues such as noise figure and intercept point as noted in Question 9 (out of 5). Based on this input, the Spring 2011 follow-on course (RF Circuit Design) covered this material again at the start of the semester.

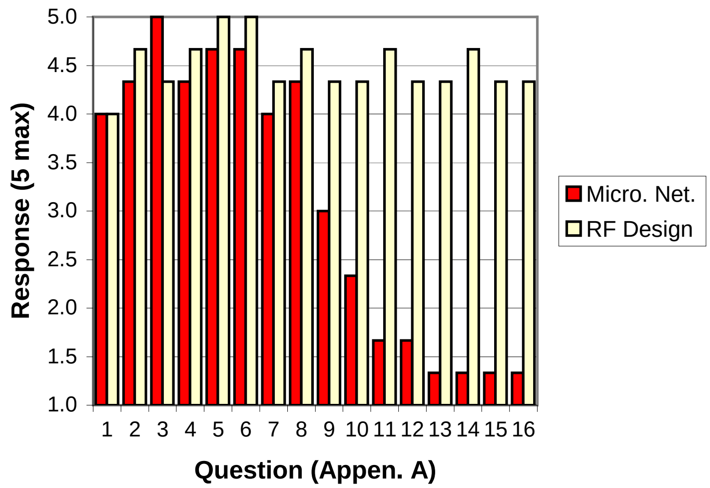

Figure 6. Level of student achievement in the senior elective in the Microwave and RF design sequence (first course: Microwave Networks; second course: RF Circuit Design).

The follow-on course in RF Circuit Design started off with the lower level of achievement in the material assessed in Questions 10-16 as shown in Figure 6 (amber bars) since this material was not significantly covered in Microwave Networks. An assessment was performed near the end of the RF section of the course in these areas with a significant improvement in student's perceptions of enhancement of skills and with little loss of skills gained in the previous course. Of note was the improvement in Question 9 (system issues), indicating a positive outcome to a review of this material a second time. The evidence of skills enhancement related to Questions 1, 3, 5-11, 13, 14, and 16 was further supported by the results of the final course project (described earlier with an example shown in Figure 3). In this project, students were required to design the input bandpass filter using both lumped and distributed elements which required not only the necessary filter design skills from the previous course but also newer material in resonator filters. Measurements on this filter indicated insertion loss of less than 0.3dB at the center frequency with at least 25dB stop band rejection. The amplifier design and fabrication required enhanced skills in understanding (and designing with) amplifier S-parameters as well as determining bias points and low RF loss DC bias circuits. Measurements of the amplifier indicated the students achieved gains within approximately 1.5dB of those indicated by simulation (simulations indicated approximately 11.5-12dB gain with all students achieving at least 10dB of gain) at the 900MHz design frequency. The mixer skills enhancement was further supported by the design of a single balanced mixer using a 90^o coupler (branched line coupler) and a single packaged part for the diodes (Figure 3). In addition to these skills, the student also learned valuable prototyping skills; namely, developing microstrip layouts on FR-4 as well as soldering very small surface mount, high frequency components.

Conclusion

This paper has presented details of the Microwave and RF Design Program for undergraduates at Villanova University. The program has been in operation in its present two-semester sequence for approximately five years and has shown through quantitative assessment that students are learning and understanding the basic concepts in this area that will form the basis for their continued education in this technical area. During this time, the course has spawned interest in independent studies of other technology areas not covered in depth in the two course sequence, primarily high efficiency power amplifiers, a topic not covered elsewhere in the curriculum but an important topic to the wireless systems community.

Acknowledgement

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[8] <u>RF Power Amplifier Design for Wireless Communications</u>, S. Cripps, Artech House, 2006

Appendix A

First course: Describe the level the course enhanced your knowledge of microwave and RF networks and systems from what you knew entering the course in the following areas.

1. Transmission Line Theory
2. Smith Chart
3. Narrow Band Impedance Matching
4. Wideband Impedance Matching
5. Lumped Element Filter Design
6. Distributed Element Filter Design

7. Practical strip-style Transmission Lines
8. Ability to design, fabricate and test a circuit for use above 500 MHz
9. Noise Figure, Intercept Point as system specifications

Second course: Describe the level of your knowledge of microwave and RF networks and systems from what you knew entering the course in the following areas.

10. Understanding of various receiver architectures such as direct conversion, heterodyne, low IF
11. Design of VHF amplifier hardware
12. Design of VHF oscillator hardware
13. Design of VHF mixer hardware
14. Theoretical understanding of VHF amplifier design
15. Theoretical understanding of VHF oscillator design
16. Theoretical understanding of VHF mixer design

Appendix B: Table of Abbreviations

Abbreviation	**Name**
BPF	Band Pass Filter
CAD	Computer Aided Design
dB	Decibel (or deciBel)
I/Q	In-phase/Quadrature
IF	Intermediate Frequency
ITRS	International Technology Roadmap for Semiconductors
LC	Inductor (L)-Capacitor (C)
LNA	Low Noise Amplifier
LO	Local Oscillator
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PA	Power Amplifiers
PAE	Power Added Efficiency
PC	Personal Computer
PCB	Printed Circuit Board
RF	Radio Frequency
RFID	Radio Frequency Identification
SDR	Software Defined Radio
SPICE	Simulation Package with Integrated Circuit Emphasis
SWR	Standing Wave Ratio
VHF	Very High Frequency
WiMAX	Worldwide Interoperability for Microwave Access