Chapter 7

Conclusions

The disseration has presented the systematic design of a direct conversion CMOS radio receiver for wireless LAN applications. The techniques presented in earlier chapters have enabled the implementation of a 2.4-GHz low-power CMOS direct conversion receiver in a 0.25-μm technology. To conclude, we briefly summarize the key contributions presented in previous chapters.

7.1 Summary

The specifications of the WLAN standards have been described in Chapter 2. The requirements have been mapped into receiver parameters such as noise figure and linearity requirements to give brief sketch of the receiver performance. The requirements for a dual-band receiver for WLAN and the link budget has been analyzed.

Chapter 3 has presented a dual-band switchable low noise amplifier (LNA) implemented in 0.25-μm CMOS technology for 5-GHz wireless multimedia applications. With a PMOS varactor together with the inductor as a dual-band switchable load, the LNA can be operated at the lower band or the upper band at 5-GHz by 1-bit control signal at the PMOS gate. The dual-band switchable load enables the LNA operate at the lower or the upper band at 5-GHz band by a 1-bit control signal. The LNA exhibits over 17 dB power gain, 3.5 dB noise figure and input 1-dB compression point −23 dBm in both frequency bands. It draws 9.5 mA from 2.5 V supply. The power gain remains larger than 16 dB as temperature varies from −5 to 65°C.

A current-folded mixer topology, which uses a capacitor to separate the bias current of input stage and switching stage and employs an inductor to replace tail current source of the switching pair has been presented in Chapter 4. The mixer decouples the noise and linearity design tradeoff and exhibits higher conversion gain, higher linearity and lower noise figure than conventional current-reused injection topology.

For the RF/baseband co-verification, Chapter 5 has presented the necessity of RF/baseband co-simulation and the co-verification platform. The case study of a 2.4-GHz RF receiver front-end has been presented in Chapter 6 to demonstrate the feasibility of the RF/baseband co-verification design methodology.

7.2 Recommendations for Future Work

The current-folded mixer employs a spiral inductor which expands the circuit area. The optimization of spiral inductors could helps to reduce the area. In addition, the 1/f noise modeling of MOS devices is critical to the mixer design and the modeling should be improved. Moreover, RF/baseband co-verification provides reasonable prediction of the system performance but the computing time increases as the system complexity increases, which should be improved in order to reduce the co-verification cycle.

Appendix A

EVM and SNR

Figure A.1 depicts the concept of error vectors. The transmitted signal and received signal are regarded as vectors, **s** and **r**. The error vector between the received and transmitted vectors is **e**. The received signal is related to the error vector as follows,

$$\mathbf{r} = \mathbf{s} + \mathbf{e}. \tag{A.1}$$

representing the desired signal plus the error. If the error is caused by noise, then we can take the error vector as a noise vector. The received vector can be expressed by

$$|\mathbf{r}| = \sqrt{x^2 + y^2} \tag{A.2}$$

where $x = |\mathbf{s}| + |\mathbf{e}| \cos\phi$, and $y = |\mathbf{e}| \sin\phi$.

EVM is the normalized error vector magnitude,

$$EVM = \frac{|\mathbf{e}|}{|\mathbf{s}|}. \tag{A.3}$$

The signal to noise ratio (SNR) is the relative retio of the signal level and the noise level, i.e.

$$SNR = \frac{|\mathbf{s}|^2}{|\mathbf{e}|^2}. \tag{A.4}$$

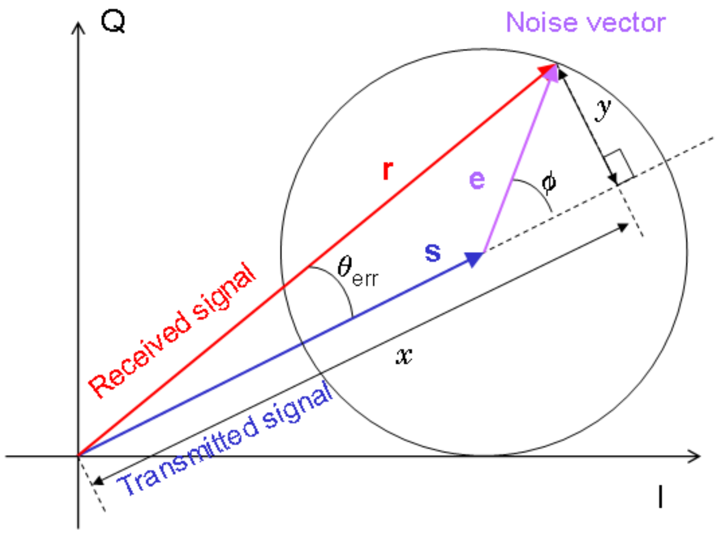

Figure A.1: Error vector.

Hence SNR is related to EVM as

$$SNR = \frac{1}{EVM^2}. \tag{A.5}$$

Note that noise is random and not deterministic and the representations of noise $n(t)$ and error vectors e(t) are required to express in their average forms. That is, take the time average values of the squared noise or error vector for a long period T as the mean-square power, or

$$< n^2(t) >= \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} n^2(t)dt. \tag{A.6}$$

Typically, most of the random phenomena in RF systems can be considered stationary and the statistical properties of noise or errors are invariant to a time shift. Therefore, EVM and SNR equations are also required to express in the time average forms.

Appendix B

An Implementation of 2.4-GHz Low Noise Amplifier

A 2.4-GHz low-noise amplifier was implemented in 0.25 μm CMOS to verify the performance of RF device cell library developed in our lab. The schematic is depicted in Figure B.1. The design equations of noise figure and power gain can be analyzed and each devices in the schematic can be determined.

$$F = 1 + \frac{R_l}{R_s} + \frac{R_G}{R_s} + \frac{\gamma}{\alpha}\frac{1}{R_s}\frac{1}{g_m}\frac{1}{Q_{in}^2} \tag{B.1}$$

$$A_v = -\frac{g_m Q_{in}}{G_{tot}} A_{buf} \tag{B.2}$$

where Q_{in} is the quality factor of the input matching resonator. These design equations must take into account the parasitic effects of the RF device cells such as gate resistance R_G of MOSFET and series resistance of spiral inductors, R_l. The G_{tot} is the total conductance of the drain node of M_2; in order to increase the voltage gain, the G_{tot} should be minimized or equivalently increase Q_{L1} of the spiral inductor L_1 since

$$\frac{1}{G_{tot}} = \left(1 + Q_{L1}^2\right) R_{L1}, \tag{B.3}$$

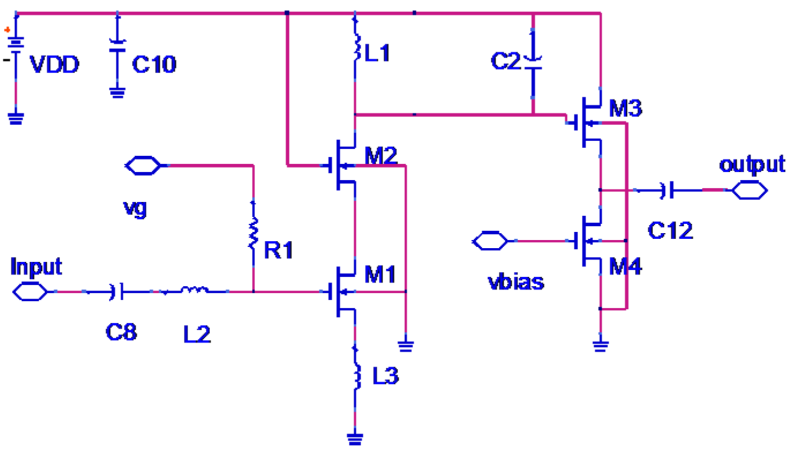

Figure B.1: 2.4-GHz low noise amplifier schematic.

where R_{L1} is the series parasitic resistance of inductor L_1. Both the noise figure and power gain are affected by the quality factors of inductors.

Assuming the spiral inductors are modeled by a parasitic R in series with a inductance L, the quality of the spiral inductor can be expressed as

$$Q = \frac{2\pi f L}{R} \tag{B.4}$$

$$R \in \text{Constant} \Rightarrow Q \propto f \tag{B.5}$$

$$R \propto f \Rightarrow Q \in \text{Constant} \tag{B.6}$$

$$R \propto \sqrt{f} \Rightarrow Q \propto \sqrt{f} \tag{B.7}$$

The Q of the spiral inductor cells in the cell library can be estimated via the above equations. Design the circuits with these Q-estimated inductor models to meet the design specifications, one must add additional design margin over the original design specification. The design margin is reserved for compensating the performance degradation caused by the over estimation of the Q factors when replacing the real spiral cells. For low noise amplifier design, the additional power gain design margin is given by

$$M = -10 \log \left(\frac{1 + \overline{Q_{cell}^2}}{1 + \overline{Q_{estimated}^2}} \right) \tag{B.8}$$

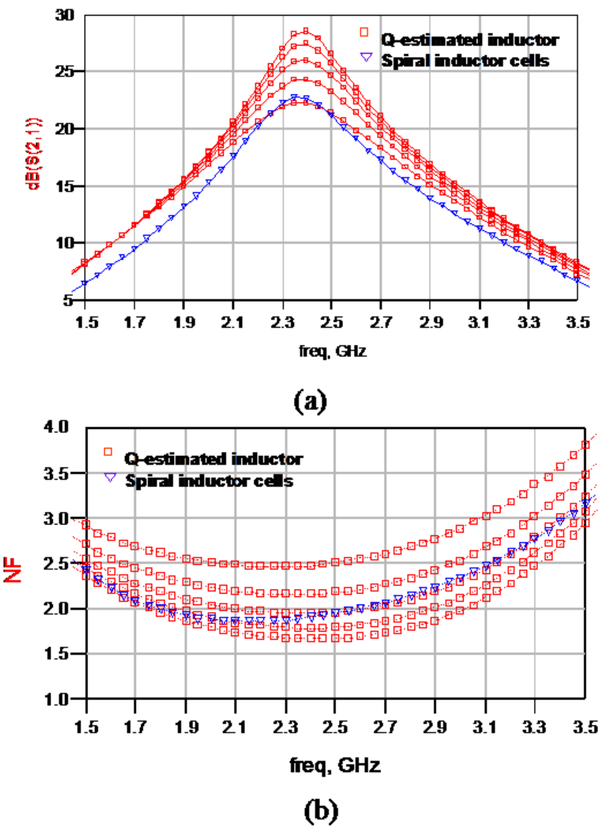

Figure B.2: Simulation results: (a) power gain (b) noise figure; compared Q estimation of 5 to10 with RF spiral cells.

where Q_{cell} is the weighted mean quality factor of the spiral inductors in the RF cell library and $Q_{estimated}$ is the estimation for the spiral inductors in the circuits. For example, designing a 20-dB LNA with the estimated Q of 10 for the spiral cell Q ranges from 4 to 7, the design margin should be 5∼6 dB higher. Figure B.2 compares the power gain and noise figure simulation results for the LNA designed with Q-estimated inductors and that with RF spiral cell library replaced.

The photograph of the low noise amplifier is shown in Figure B.3. The measurement is performed by on-wafer probing. The measured noise figure and power gain results are shown in Figure B.4. The LNA exhibits 20 dB power gain and 2.6 dB noise figure.

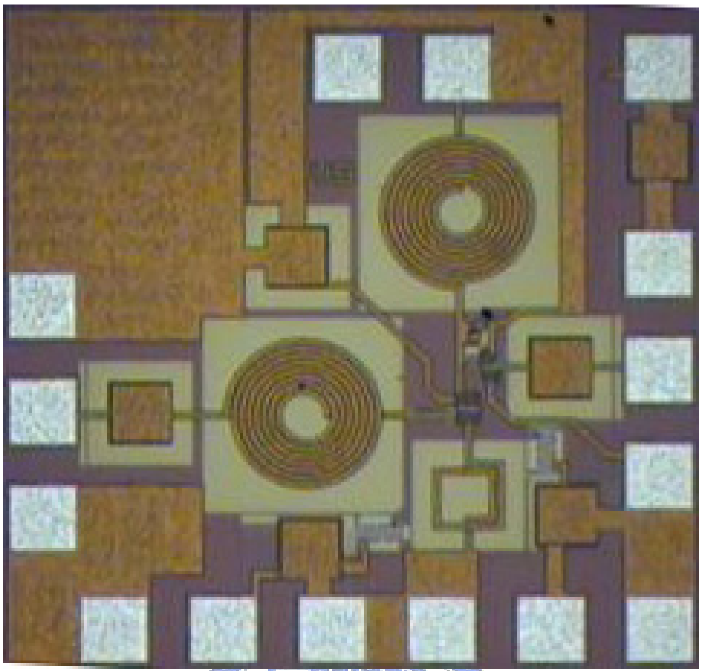

Figure B.3: 2.4-GHz low noise amplifier photograph.

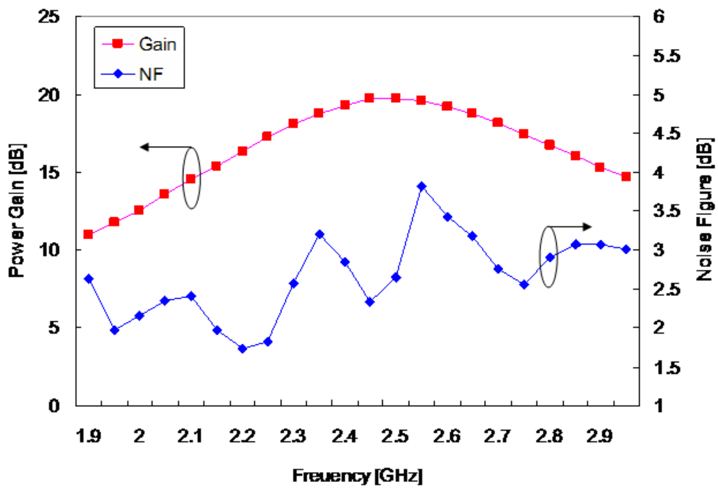

Figure B.4: The measured noise figure and power gain of the LNA.

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自 傳 - Vita

溫 文 燊 — Wen-Shen Wuen

新竹縣新豐鄉新興路57號 — 57 Hsinsing Rd., Hsinfeng, Hsinchu County, Taiwan

+886-3-5591887 — wswuen.ee87g@nctu.edu.tw

學 歷 — Educations

- 國立交通大學 電子研究所 博士班 — 1998-2004
  Ph.D., Institute of Electronics, National Chiao Tung University — Hsinchu, TW
- 國立交通大學 電子研究所 碩士班 — 1996-1998
  M.S., Institute of Electronics, National Chiao Tung University — Hsinchu, TW
- 國立交通大學 電子工程學系 — 1992-1996
  B.S., Dept. of Electronics Eng., National Chiao Tung University — Hsinchu, TW
- 台北市立建國高級中學 — 1989-1992
  Chien Kuo Senior High School — Taipei, TW

經 歷 — Experiences

- 研究顧問 智森科技股份有限公司 — 2003.5-11
  Research Consultant, Giga Solution Tech. Ltd. — Hsinchu, TW
- **ADS** 訓練課程講師 台灣安捷倫科技股份有限公司 — 2001.6-2002.5
  ADS Trainging Course Instuctor, Agilent Technology — Chungli, TW
- 實習工程師 台灣積體電路股份有限公司 — 1998.7-8
  Summer Intern, Taiwan Semiconductor Manufacture Corp. — Hsinchu, TW
- 活動組長 交大電子系第八屆微電子營 — 1995.7
  Activity Team Leader, 8th Microelectronics Camp, EE/NCTU — Hsinchu, TW
- 隊長 救國團基層文化服務隊-南投縣信義鄉 — 1994.2
  Captain, CYC Grossroot Culture Service Camp — Nantou, TW

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