Journal of Electronic Research and Application, 2025, Volume 9, Issue 7
http://ojs.bbwpublisher.com/index.php/JERA
ISSN Online: 2208-3510
ISSN Print: 2208-3502

High-Frequency Analog Signal Processing in Integrated Circuits

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Abstract: This paper focuses on high-frequency analog signal processing in integrated circuits, encompassing key aspects such as electromagnetic wave propagation in semiconductor media, device modeling, circuit architecture, noise modeling, and power integrity. It analyzes the influence of these factors on signal processing performance and discusses corresponding technical approaches. In addition, the paper addresses representative applications in 5G communications, automotive radar, and medical imaging systems. Future research directions in high-frequency analog integrated circuit design are also discussed.

Keywords: High-frequency analog signal processing; Integrated circuits; Circuit architecture

Online publication: December 31, 2025

1. Introduction

With the rapid development of modern science and technology, such as the 5G related policies issued in 2019 to promote the continuous upgrading of communication technology, high-frequency analog signal processing has become crucial in many fields. In the field of integrated circuits, high-frequency analog signal processing is closely related to the propagation characteristics of electromagnetic waves in semiconductor media, the establishment of high-frequency equivalent circuit model of devices, and the analysis of various high-frequency analog circuit architectures. At the same time, in the communication system, high-frequency analog signal processing plays a key role in the design of 5G millimeter wave front-end and the application of carrier aggregation technology, the signal generation and multi-target detection algorithm of automotive radar system, as well as the ultrasonic probe driving circuit and bioelectrical signal acquisition of medical imaging equipment, and faces many technical challenges and research directions.

2. Theoretical basis of high frequency analog signal processing

2.1. Analysis of high frequency signal transmission characteristics

The propagation of electromagnetic wave in semiconductor medium follows Maxwell equations. In the case of high frequency, the conductivity and dielectric constant of semiconductors will have a significant impact on the propagation characteristics. Skin effect is a phenomenon that cannot be ignored in high-frequency signal transmission. With the increase of frequency, the current tends to flow on the surface of the conductor, resulting in the increase of the effective resistance of the conductor, and then affecting the amplitude and phase of the signal [1]. Dielectric loss also has an important impact on signal integrity, which will make the signal energy gradually attenuate in the transmission process. In order to accurately describe the behavior of high-frequency signals in the transmission line, it is necessary to establish the transmission line model. The model considers the distributed parameters of transmission lines, such as inductance, capacitance and resistance, and can effectively analyze the reflection, refraction and transmission delay of signals.

2.2. Physical model of semiconductor devices

MOSFET and BJT are commonly used semiconductor devices in integrated circuits. In the high-frequency working state, its characteristics will change, so it is necessary to establish an equivalent circuit model to accurately describe it. For MOSFET, considering the capacitance effect at high frequency, such as the capacitance between gate and channel, these capacitors will affect the signal transmission and processing. By analyzing the physical process of the device, the high frequency equivalent circuit model can be derived [2]. The same is true for BJT. The carrier motion in BJT will be affected by many factors at high frequencies, such as base width modulation effect. Transconductance parameter is an important index to describe the performance of devices. At high frequency, it has a nonlinear relationship with the frequency response. This is because with the increase of frequency, various parasitic parameters such as capacitance and inductance inside the device begin to work, changing the transmission characteristics of the signal, resulting in the nonlinear changes of transconductance parameters and frequency response.

3. Design method of high frequency analog circuit

3.1. Low noise amplifier architecture

Common source common gate structure and differential amplifier structure are common low noise amplifier architectures in high frequency analog circuits. The cascode structure has high gain and good isolation performance, but the noise figure may be relatively high. Differential amplifier has advantages in suppressing common mode noise, but there may be bandwidth limitation in some high frequency applications. By comparing the noise figure of the two structures, we can better understand their performance characteristics in different application scenarios. The design method of broadband low noise based on current reuse technology is an effective improvement method. This method can improve the bandwidth of the amplifier and reduce the noise figure without increasing too much power consumption, so as to improve the performance of the whole circuit. It is suitable for the design of high-frequency analog circuits with high requirements for noise and bandwidth [3].

3.2. Mixer linearity optimization

As a common mixer structure, the nonlinear distortion of Gilbert cell has a significant impact on the linearity of mixer. By studying the nonlinear distortion mechanism, the key to optimize the linearity can be found. The harmonic balance equation is an effective method, which can accurately describe the nonlinear behavior in the circuit and provide a theoretical basis for analysis and optimization. Based on the results of harmonic balance equation, a predistortion compensation network is designed to compensate the nonlinearity of Gilbert cell. The predistortion compensation network can make the output signal after passing through the Gilbert cell closer to the ideal linear output by introducing the distortion component opposite to the nonlinear distortion into the input signal. This method has important application value in improving the linearity of mixer [4].

4. Breakthroughs in key technologies of high-frequency circuits

4.1. Noise suppression technology

4.1.1. Substrate coupling noise modeling

The establishment of three-dimensional electromagnetic field simulation model is an important means of substrate coupling noise modeling. Through this model, the interference path of substrate noise to RF front-end can be accurately and quantitatively analyzed. The physical properties and electrical parameters of the substrate should be considered, which have a significant impact on the noise propagation. At the same time, it is necessary to accurately model the RF front-end components, including transistors, inductors, capacitors, etc., to reflect their behavior at high frequencies. In the model, the coupling effect between different components and the influence of substrate noise on the performance of RF front-end through these coupling paths should also be considered. Through the establishment and analysis of this model, we can deeply understand the generation mechanism and propagation characteristics of substrate coupling noise, and provide a theoretical basis for subsequent noise suppression technology [5].

4.1.2. Power integrity optimization

In the aspect of power integrity optimization, the design of distributed decoupling capacitor array is one of the key technologies. By reasonably distributing decoupling capacitors, the noise of power supply can be effectively reduced and the stability of power supply can be improved. This design can suppress the power supply noise at different positions to avoid excessive local noise affecting the circuit performance [6]. Concurrently, a power network impedance matching method based on transfer matrix is proposed. By accurately calculating and adjusting the impedance of the power network, the method makes it match with the load impedance. This can reduce signal reflection, improve power transmission efficiency, further ensure the normal operation of high-frequency circuit, and provide a stable power environment for high-frequency analog signal processing.

4.2. Power management strategy

4.2.1. Adaptive bias control

Adaptive bias control is very important in the power management strategy of high frequency circuits. By developing a dynamic threshold voltage regulation algorithm, the real-time optimization of power amplifier efficiency with signal envelope can be realized. This adaptive control method can dynamically adjust the bias according to the real-time changes of the signal, so that the power amplifier can maintain high efficiency under different signal strengths. On one hand, it avoids excessive power consumption caused by fixed bias at low signal strength. On the other hand, it can also ensure the normal operation and efficient operation of the amplifier under high signal strength. This technological breakthrough provides an effective solution for the power management of high-frequency circuits and helps to improve the performance and energy efficiency ratio of the whole high-frequency circuit system [7].

4.2.2. Temperature compensation circuit

In order to solve the problem of temperature drift in high frequency circuits, a cross temperature stability compensation scheme combining bandgap reference and thermistor network is designed. The bandgap reference has the characteristic that the output voltage is basically constant within a certain temperature range, and can provide a stable reference voltage [8]. The thermistor network can sense the change of temperature and cooperate with the bandgap reference through reasonable circuit design. When the temperature increases or decreases, the resistance value of the thermistor changes, and then the current or voltage in the circuit is adjusted to keep the performance parameters of the whole circuit relatively stable. This combination method can effectively compensate the circuit parameter deviation caused by temperature change in a wide temperature range, and improve the stability and reliability of high-frequency circuit in different temperature environments.

5. Analysis of typical application scenarios

5.1. 5G communication system

5.1.1. Millimeter wave front end design

In 5G communication system, millimeter wave front-end design is very important. Taking a 28 ghz band four channel beamforming transceiver as an example, it integrates a phase shifter and a variable gain amplifier module. In the millimeter wave band, due to the shorter wavelength, higher antenna gain and smaller antenna size can be achieved, which provides good conditions for the application of multi antenna technology. By adjusting the phase and amplitude of each antenna element in the antenna array, beamforming technology can realize the directional transmission and reception of signals, and improve the performance and capacity of the communication system. The phase shifter is used to precisely control the phase of the signal, and the variable gain amplifier module can adjust the amplitude of the signal. This integrated design can better meet the requirements of 5G communication system for high speed, large capacity and low delay, and improve the reliability and effectiveness of millimeter wave band communication [9].

5.1.2. Carrier aggregation technology

In 5G communication system, carrier aggregation technology has important applications. Taking the development of a reconfigurable low noise amplifier supporting 3.5 ghz + 4.9 ghz dual band concurrent operation as an example, carrier aggregation technology can realize the integration of multiple bands. Through this technology, carrier resources of different frequency bands can be aggregated to improve spectrum utilization [10]. In this scenario of dual band concurrent operation, the reconfigurable low noise amplifier uses carrier aggregation technology to effectively reduce noise interference and improve signal reception quality. It can flexibly adjust its parameters and working mode according to the characteristics and requirements of different frequency bands to ensure efficient signal amplification and processing in both frequency bands. This is essential to meet the requirements of 5G communication system for high-speed data transmission and high-quality communication, and provide users with a more stable and faster communication experience.

5.2. Automotive radar system

5.2.1. FMCW signal generation

In automotive radar system, FMCW signal generation is very important. The 76-81 ghz LFM source based on

PLL is the key part. This frequency band is applicable to the detection requirements of automotive radar. Through the reasonable design of phase-locked loop, the generation of high-frequency LFM signal can be realized. In terms of phase noise, it is optimized to -95dbc/ Hz@1MHz Level of. Low phase noise can improve the resolution and accuracy of radar system. In the process of vehicle driving, radar needs to accurately detect the distance and speed of surrounding vehicles and obstacles. The high-quality generation of FMCW signal can make the radar system better process the reflected signal, so as to accurately determine the relevant information of the target. It plays a key role in the realization of active safety system, such as automatic emergency braking, adaptive cruise and other functions.

5.2.2. Multi-target detection algorithm

In the multi-target detection algorithm of automotive radar system, it is of great significance to develop a signal processing architecture combining fast Fourier transform and constant false alarm rate detection. The fast Fourier transform can transform the time-domain signal into the frequency-domain signal, and effectively extract the frequency characteristics of the signal. Through this conversion, we can better analyze the frequency components of different targets in radar echo, and provide the basis for target discrimination and recognition. CFAR detection is used to maintain the stability of false alarm probability in complex noise environment. By adaptively adjusting the detection threshold, it can avoid excessive misjudgments caused by noise fluctuations. The combination of the two can make full use of the frequency analysis advantage of fast Fourier transform and the anti-noise ability of constant false alarm rate detection, so as to accurately detect multiple targets and improve the target detection performance of automotive radar system in complex traffic environment.

5.3. Medical imaging equipment

5.3.1. Driving circuit of ultrasonic probe

In medical imaging equipment, the driving circuit of ultrasonic probe is very important. For the high-voltage pulse generator and receiver front-end integrated module with 120 dB dynamic range under 15 MHz bandwidth, it has a unique application in ultrasonic probe drive. The circuit can provide appropriate electrical signal excitation for the ultrasonic probe, so that the probe can emit ultrasound that meets the imaging requirements. In the launch phase, the high-voltage pulse generator generates high-voltage pulse signal, drives the piezoelectric crystal of the ultrasonic probe to vibrate, and generates ultrasonic wave to spread to human tissues. The receiving front-end integration module is responsible for receiving the weak ultrasonic signal reflected back, and performing amplification, filtering and other processing to extract useful imaging information. The application of this integrated module in the ultrasonic probe driver circuit can improve the resolution and clarity of ultrasonic imaging, and better assist doctors in the diagnosis of human internal tissues and organs.

5.3.2. Bioelectrical signal acquisition

Micro power consumption instrument amplifier plays a key role in the acquisition of bioelectrical signals in medical imaging equipment. It realizes the characteristics of 0.8 μ VRMs input reference noise in the frequency band of 0.5–100Hz, and can effectively collect weak bioelectrical signals. For the acquisition of bioelectrical signals such as electrocardiogram (ECG), weak electrical signals need to be accurately amplified and noise interference should be reduced as much as possible. The low-power characteristics of the amplifier also meet the requirements of medical devices for energy efficiency, especially in some wearable or portable medical imaging devices, which can prolong the service time of the device. At the same time, its good performance in a specific frequency band ensures the accuracy and integrity of the collected bioelectrical signals, and provides a reliable data basis for subsequent medical diagnosis.

6. Conclusion

High frequency analog signal processing in integrated circuits covers many important aspects. In terms of theory and technology, the theoretical system of high-frequency analog circuit design and its technological evolution path are systematically summarized, which lays the foundation for subsequent research. At the same time, the marginal effect of CMOS process node scaling on circuit performance is deeply summarized, which is helpful to better understand the impact of process changes. Aiming at the existing problems, a three-dimensional packaging solution based on heterogeneous integration is proposed, which provides a new idea for improving the circuit performance. In addition, the development direction of the integration of new compound semiconductor devices in terahertz band application scenarios is prospected, which will guide the focus and direction of future research, and is of great significance for the application of high-frequency analog signal processing in integrated circuits in more advanced frequency bands.

Disclosure statement

The author declares no conflict of interest.

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