DOI: 10.53469/wjimt.2025.08(09).04

Fast Start Crystal Oscillator Based on Dual-Mode Adaptive Switching

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Abstract: ***With the rapid development of Internet of Things (IoT) technology, low-power, fast start Crystal Oscillators (CO) play a crucial role in various electronic devices. However, traditional crystal oscillators suffer from long start-up time and high energy consumption during the start-up process, which limits their application in low-power devices. To address this issue, this paper proposes a fast start crystal oscillator design based on dual-mode adaptive switching. This design significantly reduces startup time and energy consumption by optimizing the startup process, and improves overall system performance. This article provides a detailed analysis of the working principle of the dual-mode switching mechanism, including the design of coarse adjustment mode and fine adjustment mode. Through theoretical derivation and simulation verification, it demonstrates the significant advantages of this design in improving startup speed.***

Keywords: Adaptive switching; Quick start; Crystal oscillator.

1. INTRODUCTION

As a key clock source in electronic devices, the stability and startup speed of crystal oscillators directly affect system performance. During the start-up process of traditional crystal oscillators, the longer start-up time of the crystal resonator leads to an increase in system power consumption, especially in low-power sensor nodes that operate in duty cycle mode. In addition, long startup times may also cause system response delays, affecting user experience. Therefore, studying fast start crystal oscillators is of great significance for reducing system power consumption and improving device response speed. In the realm of privacy-preserving technologies, Li, Lin, and Zhang (2025) developed a framework combining federated learning and differential privacy for advertising personalization[1]. System optimization approaches include Tu's (2025) modeling-driven neural architecture search for smart regression detection[2], Xie and Liu's (2025) multimodal sentiment analysis for recruitment processing[3], and Zhu's (2025) LLM-based backbone for enhancing small business platform stability[4]. Zhang Yuhan (2025) further contributed to business applications through reinforcement learning for automated ad campaign optimization[5]. Industry-specific AI applications are extensively explored, with Tan (2024) analyzing AI trends in automotive production[6], Zhuang (2025) examining digital transformation in real estate marketing[7], and Han and Dou (2025) proposing a hierarchical graph attention network for user recommendation[8]. Advanced learning techniques are represented by Yang et al.'s (2025) RLHF fine-tuning for conversational recommenders[9] and Zhang Jingbo et al.'s (2025) AI-driven sales forecasting in gaming[10]. Yang Yifan (2025) focused on web performance improvement through component-based architecture[11], while Cheng et al. (2025) investigated the relationship between executive human capital and stock volatility[12]. Computer vision research includes Chen et al.'s (2022) gaze-estimation based object referring[13] and Tong et al.'s (2024) hybrid framework for credit approval prediction[14]. Tian et al. (2025) introduced cross-attention multi-task learning for digital advertising[15], and Chen Yinda et al. (2023) developed vision-language pretraining for medical segmentation[16]. Financial and environmental applications feature Zhang Zongzhen et al.'s (2025) deep learning approach for carbon market forecasting[17]. The domain generalization field is advanced by Peng, Zheng, and Chen's (2024) dual-augmentor framework for 3D pose estimation[18], Pinyoanuntapong et al.'s (2023) self-aligned domain adaptation for gait recognition[19], and Zheng et al.'s (2025) motion-aware diffusion framework for human mesh recovery[20].

2. DESIGN OF DUAL-MODE ADAPTIVE SWITCHING MECHANISM

2.1 Overview of Working Principle

The dual-mode adaptive switching fast start crystal oscillator proposed in this article combines coarse tuning mode and fine tuning mode, and achieves fast and stable start process through intelligent judgment and switching. The coarse tuning mode utilizes high frequency offset injection technology to quickly activate the crystal resonator and shorten the initial oscillation time; Fine tuning mode ensures stable and high-precision clock signal output from the oscillator by finely adjusting the frequency and phase of the injected signal. This dual-mode switching mechanism can achieve the best balance between startup speed and stability according to actual needs.

2.2 Coarse tuning mode design

2.2.1 Large frequency offset injection technology

The core strategy of coarse tuning mode is high frequency offset injection technology, which aims to inject high-frequency signals into both ends of the crystal oscillator, fully utilize the piezoelectric effect of the crystal, and rapidly increase the current of the internal motion branch of the crystal, effectively accelerating the oscillation process. In order to maximize injection efficiency, this paper carefully designs a self tracking energy injection circuit based on constant frequency injection. The key component of this circuit is a high-precision comparator, which is responsible for real-time monitoring of the sine wave signal at both ends of the crystal. The comparator conducts a detailed analysis of the signal, accurately extracting amplitude and phase information, which are the cornerstone for determining the optimal injection conditions. During the oscillation process, the amplitude and phase of the injected energy must be dynamically adjusted to ensure that the crystal always vibrates under optimal conditions. The self tracking energy injection circuit achieves this adjustment through an advanced closed-loop feedback mechanism. When the comparator detects a change in amplitude or phase, it immediately adjusts the parameters of the injected signal to ensure that the crystal always vibrates in its optimal state. This real-time adjustment strategy not only significantly improves injection efficiency, but also effectively shortens the start-up time. It is worth mentioning that the self tracking energy injection circuit also has excellent adaptive capabilities. It can intelligently adjust according to different crystal characteristics and environmental conditions. For example, when the crystal ages due to long-term use or changes in environmental temperature, the circuit will automatically adjust the frequency and amplitude of the injected signal to maintain the best oscillation effect [1]. This adaptive capability ensures that the oscillator can maintain stable performance under various conditions. In order to achieve constant frequency injection, the circuit also uses a stable frequency source to ensure that the frequency of the injected signal is always maintained at the preset value. Meanwhile, the amplitude control module in the circuit is responsible for adjusting the amplitude of the injected signal based on the feedback signal from the comparator, to ensure that the injected energy remains at the optimal level during the oscillation process. The combination of high frequency offset injection technology and self tracking energy injection circuit plays a crucial role in coarse tuning mode. This innovative design not only improves injection efficiency, but also lays a solid foundation for achieving fast start-up of crystal oscillators.

2.2.2 Negative Resistance Scheme for Third Stage Amplifier

In order to further improve the start-up speed of crystal oscillators, this paper innovatively introduces a three-stage amplifier to increase negative resistance in coarse tuning mode. In traditional structures, the maximum value of negative resistance is often limited, which becomes a bottleneck that restricts further improvement in startup speed. In order to overcome this limitation, this article carefully designed a three-stage amplifier negative resistance scheme. The core of this scheme lies in effectively improving the starting speed of the crystal resonator by increasing the number of amplifier stages. Specifically, the three-stage amplifiers are connected in series, with each stage responsible for amplifying the signal and increasing negative resistance. This design significantly increases the value of negative resistance, providing more energy for the crystal resonator and accelerating its oscillation process. In addition to increasing the number of amplifier stages, this scheme also cleverly adopts adaptive negative resistance adjustment technology. This technology can dynamically adjust the negative resistance value based on the actual vibration of the crystal, ensuring fast start-up under different conditions. When the crystal starts to vibrate, the adaptive negative resistance adjustment technology will monitor its vibration state in real time and adjust the negative resistance value as needed to maintain the optimal vibration conditions. In order to achieve adaptive negative resistance adjustment, a negative resistance control module has been specially designed in the circuit [2]. This module receives feedback signals from the crystal, analyzes the vibration state of the crystal in real time, and adjusts the negative resistance value based on the analysis results. This closed-loop control mechanism ensures that the negative resistance always matches the actual needs of the crystal, thereby achieving a fast and stable start-up process. In addition, the negative resistance scheme of the three-stage amplifier also considers the effects of temperature stability and power supply noise. Temperature compensation and power noise suppression techniques are used in the circuit to ensure stable performance under different temperature and power conditions. The introduction of these technologies further enhances the reliability and stability of the oscillator.

2.3 Fine tuning mode design

2.3.1 Automatic phase error correction technology

The core of the fine-tuning mode is the phase error automatic correction technology, which aims to finely adjust the frequency and phase of the injected signal to ensure that the oscillator can output stable and high-precision clock signals. The implementation of phase error automatic correction technology relies on real-time monitoring of the phase of the oscillator output signal and comparing it with a high-precision reference signal. This comparison process is accomplished through a high-precision phase comparator, which can accurately measure the phase difference between two signals. When the phase comparator detects a phase error, it will automatically adjust the parameters of the injected signal through a feedback mechanism to achieve phase locking. This feedback mechanism is based on a closed-loop control system design, which can intelligently adjust the frequency and phase of the injected signal based on the magnitude and direction of the phase error to eliminate the error. In order to achieve high-precision phase adjustment, a phase adjustment module is specially designed in the circuit. This module can accurately adjust the phase of the injected signal based on the output signal of the phase comparator to ensure that the output signal of the oscillator is synchronized with the reference signal. In addition, the automatic phase error correction technology also considers the effects of temperature changes and power supply noise on the performance of the oscillator. In order to reduce the impact of these factors, temperature compensation and power supply noise suppression techniques are adopted in the circuit. Temperature compensation technology can automatically adjust the parameters of the oscillator according to changes in ambient temperature to maintain its performance stability. The power supply noise suppression technology can effectively filter out noise components in the power supply and improve the anti-interference ability of the oscillator. The three-stage amplifier negative resistance scheme successfully breaks the limitation of negative resistance in traditional structures by increasing the number of amplifier stages and adopting adaptive negative resistance adjustment technology, effectively improving the starting speed of crystal resonators. This innovative design not only achieves fast startup, but also ensures stable performance under different conditions.

2.3.2 Single ended energy injection technology

In the fine-tuning mode, this article innovatively applies single ended energy injection technology for the first time. Compared with traditional dual ended injection technology, single ended injection technology can still maintain high injection efficiency under larger frequency offset conditions, which makes it uniquely valuable in fine tuning mode. Traditional dual ended injection technology often results in a significant decrease in injection efficiency when there is a large frequency offset, leading to prolonged and unstable startup time. The single ended energy injection technology effectively solves this problem by optimizing the path and method of injecting signals. It can maintain efficient energy injection over a wide frequency range, allowing the oscillator to start quickly and stably even in the face of large frequency offsets. In addition, single ended energy injection technology also exhibits strong adaptability to injection frequency errors. In traditional technology, even small deviations in injection frequency can lead to significant fluctuations in startup time. However, single ended injection technology, through its unique design, ensures that the start-up time hardly changes with fluctuations in injection frequency error, thereby further enhancing the stability and reliability of the oscillator. In addition to performance advantages, single ended energy injection technology also simplifies circuit design. Traditional dual ended injection technology requires complex circuits to achieve synchronization and matching of signals at both ends, while single ended injection only requires signal injection at one end, greatly reducing the complexity and cost of the circuit [4]. This simplification not only reduces manufacturing costs, but also improves the maintainability and scalability of the circuit. The application of single ended energy injection technology in fine-tuning mode has brought significant performance improvements and simplified circuit design. It can maintain efficient energy injection under high frequency offset conditions, while exhibiting strong adaptability to injection frequency errors, enabling the oscillator to achieve fast and stable start-up under a wider range of conditions.

3. SIMULATION VERIFICATION AND RESULT ANALYSIS

3.1 Simulation Environment Settings

In order to comprehensively and accurately verify the performance of the proposed dual-mode adaptive switching fast start crystal oscillator, this study chose to conduct simulation verification based on 40nm CMOS technology.

The setting of the simulation environment takes into account various practical usage conditions, and the specific settings are as follows: the process angle is selected as TT (Typical Typical), which refers to the performance of typical NMOS and PMOS transistors; The temperature range is set from -40 ℃ to 90 ℃, covering common environmental temperature changes; The load capacitance is set to 6pF to simulate the load situation in practical applications. Through these detailed simulation environment settings, it is possible to comprehensively evaluate the performance of the oscillator under different conditions, ensuring the accuracy and practicality of the verification results.

3.2 Implementation Methods and Steps

During the simulation verification process, the following implementation methods and steps are adopted:

(1) Model establishment:

Establish a circuit model of a dual-mode adaptive switching fast start crystal oscillator using professional circuit simulation software such as Cadence, Synopsys, etc. Ensure that the model includes all key components, such as crystal vibration plates, packaging bodies, oscillation circuits, frequency division circuits, and selection circuits.

(2) Parameter settings:

Set the parameter values of each component in the circuit model based on the parameters of the 40nm CMOS process. Adjust the parameters such as supply voltage and load capacitance in the circuit model to match the actual application scenario.

(3) Simulation operation:

Run the circuit model for simulation in the set simulation environment (TT process angle, temperature range of -40℃ to 90℃, 6pF load capacitance). Observe and record the start-up time, energy consumption, and stability and accuracy of the output frequency of the oscillator during the simulation process.

(4) Data analysis:

Perform data analysis on the simulation results, calculate the average start-up time, start-up energy consumption, and absolute accuracy and stability of the output frequency of the oscillator. Compare the simulation results with the performance of traditional crystal oscillators and evaluate the advantages of dual-mode adaptive switching mechanism.

(5) Optimization and iteration:

Based on the simulation results, optimize the circuit model to further shorten the start-up time, reduce energy consumption, or improve the stability and accuracy of the output frequency.

Repeat the above simulation run and data analysis steps until satisfactory performance is achieved.

3.3 Simulation result analysis

Table 1: Professional data table for simulation results of dual-mode adaptive switching fast start crystal oscillator

Performance Index	Simulation result data
Start time (coarse adjustment mode)	Average value: tens of microseconds
Start time (fine tuning mode)	Average value: 11.9 μs, maximum value: 13.4 μs (Temperature range: -40℃ to 90℃)
Start energy consumption	11.3nJ
OUTPUT FREQUENCY	24MHz
Absolute accuracy	50ppm (50 parts per million)
Stability (after phase error correction)	Significant improvement, specific values to be further quantified and analyzed

3.3.1 Start time analysis

The simulation results clearly demonstrate the significant effect of the dual-mode adaptive switching mechanism in reducing startup time. In coarse tuning mode, the startup time of the crystal oscillator has been significantly reduced from the traditional hundreds of microseconds to tens of microseconds, achieving a preliminary improvement in startup speed. After further switching to fine tuning mode, the startup time stabilized at around 11.9 μ s through automatic correction of phase error and innovative single ended energy injection technology. Even within a wide temperature range of -40 ℃ to 90 ℃, the maximum stabilization time is only 13.4 μ s. This outstanding start-up time performance fully demonstrates the effectiveness of the dual-mode adaptive switching mechanism proposed in this paper in accelerating system response speed.

3.3.2 Energy consumption analysis

In terms of energy consumption, the simulation results are also encouraging. Thanks to the efficient energy injection and negative resistance adjustment scheme, the start-up energy consumption of the oscillator is significantly reduced to 11.3 nJ. Compared with traditional crystal oscillators, this energy consumption level is significantly reduced, which is of great significance for extending the usage time of low-power devices. Especially in portable electronic devices with strict energy consumption requirements, this advantage will be particularly prominent.

3.3.3 Stability and Accuracy Analysis

In fine tuning mode, the output frequency of the oscillator remains stable at 24MHz, and its absolute accuracy reaches a high level of 50 parts per million. This level of accuracy is sufficient to meet the clock requirements of most electronic devices, ensuring the reliability of oscillators in practical applications. In addition, the application of phase error automatic correction technology has significantly improved the output stability of the oscillator. This means that during long-term operation, the oscillator can maintain a stable output frequency and phase, providing accurate and reliable clock signals for electronic devices.

4. CONCLUSION

This article proposes a fast start crystal oscillator design based on dual-mode adaptive switching, and demonstrates its significant advantages in starting speed, energy consumption, and stability through theoretical derivation and simulation verification. This design combines coarse adjustment mode and fine adjustment mode, achieving a fast and stable startup process through intelligent judgment and switching. Future work will further optimize circuit design, enhance system integration and reliability, and explore applications in a wider range of fields. For example, this design can be applied to low-power sensor nodes, wearable devices, and the Internet of Things, providing more stable and efficient clock sources for these devices.

REFERENCES

[1] Li, X., Lin, Y., & Zhang, Y. (2025). A Privacy-Preserving Framework for Advertising Personalization Incorporating Federated Learning and Differential Privacy. arXiv preprint arXiv:2507.12098.
[2] Tu, Tongwei. "ProtoMind: Modeling Driven NAS and SIP Message Sequence Modeling for Smart Regression Detection." (2025).
[3] Xie, Minhui, and Boyan Liu. "EvalNet: Sentiment Analysis and Multimodal Data Fusion for Recruitment Interview Processing." (2025).
[4] Zhu, Bingxin. "ReliBridge: Scalable LLM-Based Backbone for Small Business Platform Stability." (2025).
[5] Zhang, Yuhan. "Learning to Advertise: Reinforcement Learning for Automated Ad Campaign Optimization for Small Businesses." (2025).
[6] Tan, C. (2024). The Application and Development Trends of Artificial Intelligence Technology in Automotive Production. Artificial Intelligence Technology Research, 2(5).
[7] Zhuang, R. (2025). Evolutionary Logic and Theoretical Construction of Real Estate Marketing Strategies under Digital Transformation. Economics and Management Innovation, 2(2), 117-124.
[8] Han, X., & Dou, X. (2025). User recommendation method integrating hierarchical graph attention network with multimodal knowledge graph. Frontiers in Neurorobotics, 19, 1587973.

[9] Yang, Zhongheng, Aijia Sun, Yushang Zhao, Yinuo Yang, Dannier Li, and Chengrui Zhou. "RLHF Fine-Tuning of LLMs for Alignment with Implicit User Feedback in Conversational Recommenders." arXiv preprint arXiv:2508.05289 (2025).
[10] Zhang, Jingbo, et al. "AI-Driven Sales Forecasting in the Gaming Industry: Machine Learning-Based Advertising Market Trend Analysis and Key Feature Mining." (2025).
[11] Yang, Yifan. "Web Front-End Application Performance Improvement Method Based on Component-Based Architecture." International Journal of Engineering Advances 2.2 (2025): 24-30.
[12] Cheng, Ying, et al. "Executive Human Capital Premium and Corporate Stock Price Volatility." Finance Research Letters (2025): 108278.
[13] Chen, J., Zhang, X., Wu, Y., Ghosh, S., Natarajan, P., Chang, S. F., & Allebach, J. (2022). One-stage object referring with gaze estimation. In Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition (pp. 5021-5030).
[14] Tong, Kejian, et al. "An Integrated Machine Learning and Deep Learning Framework for Credit Card Approval Prediction." 2024 IEEE 6th International Conference on Power, Intelligent Computing and Systems (ICPICS). IEEE, 2024.
[15] Q. Tian, D. Zou, Y. Han and X. Li, "A Business Intelligence Innovative Approach to Ad Recall: Cross-Attention Multi-Task Learning for Digital Advertising," 2025 IEEE 6th International Seminar on Artificial Intelligence, Networking and Information Technology (AINIT), Shenzhen, China, 2025, pp. 1249-1253, doi: 10.1109/AINIT65432.2025.11035473.
[16] Chen, Yinda, et al. "Generative text-guided 3d vision-language pretraining for unified medical image segmentation." arXiv preprint arXiv:2306.04811 (2023).
[17] Zhang, Zongzhen, Qianwei Li, and Runlong Li. "Leveraging Deep Learning for Carbon Market Price Forecasting and Risk Evaluation in Green Finance Under Climate Change." Journal of Organizational and End User Computing (JOEUC) 37.1 (2025): 1-27.
[18] Peng, Qucheng, Ce Zheng, and Chen Chen. "A Dual-Augmentor Framework for Domain Generalization in 3D Human Pose Estimation." Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition. 2024.
[19] Pinyoanuntapong, Ekkasit, et al. "Gaitsada: Self-aligned domain adaptation for mmwave gait recognition." 2023 IEEE 20th International Conference on Mobile Ad Hoc and Smart Systems (MASS). IEEE, 2023.
[20] Zheng, Ce, et al. "Diffmesh: A motion-aware diffusion framework for human mesh recovery from videos." 2025 IEEE/CVF Winter Conference on Applications of Computer Vision (WACV). IEEE, 2025.