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應用線性插值校準之輔助數位控制振盪器於能量注入技術之快速起振40MHz晶體振盪器

A Fast-Startup 40MHz Crystal Oscillator with Linear-Interpolation Injection



隊伍名稱｜晶準時刻 CrysTime

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研究領域

類比、混合信號、射頻電路設計，包含時脈與頻率產生電路、資料轉換器電路、感測器與生醫應用晶片、無線通訊晶片設計等。

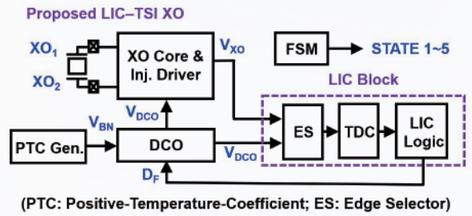
作品摘要

在物聯網(IoT)與無線通訊系統中，穩定精準的參考時脈不可或缺，其中晶體振盪器(XO)由於具備高品值因數與優異的溫度穩定性，為產生參考時脈之首選。然而，其起振時間漫長，往往需數毫秒才能達到穩定。現代IoT裝置大量採用「工作週期調控」以節省電量，裝置多處於睡眠模式，因為這類分散式節點的電池更換往往極為困難。喚醒時漫長的起振時間會白白浪費電池電量，過去的能量注入技術雖能加速，但常伴隨漫長的疊代校準與較高硬體開銷。

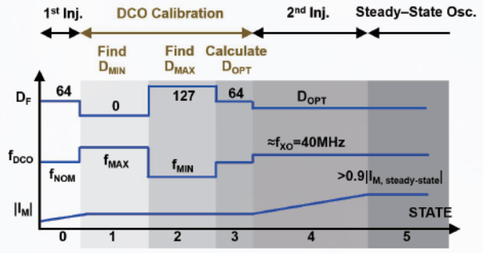
為解決此痛點，本作品提出具備「線性插值邏輯(Linear-Interpolation Injection)」校正技術的兩步驟能量注入架構，其系統架構如圖一所示。核心電路利用數位控制環形振盪器(DCO)協助產生注入能量，啟動後會先進行短暫的第一次能量注入，接著自動在DCO的最高與最低頻率下，快速量測與晶體間的頻率誤差。由於DCO週期與控制電容呈近似線性關係，系統不需耗時盲猜，而是利用線性內插數學公式，在常數時間內直接計算出準確的DCO控制訊號，使DCO頻率對齊晶體的40MHz，徹底免除傳統逐步追蹤的延遲。隨後，系統利用此頻率進行第二次強力能量注入，快速喚醒晶體，整體的快速起振過程之時序如圖二所示。

在業界應用上，此技術契合穿戴式裝置、醫療感測器、藍牙追蹤器以及智慧家庭節點。這些裝置多數時間處於休眠，若能將頻繁喚醒的準備時間從毫秒壓縮至微秒級，將能使設備電池續航力從幾個月大幅延長至數年，並顯著降低企業維護成本。

本晶片採用TSMC 90奈米製程製造，實測平均功耗僅70微瓦特。在攝氏-40至125度寬溫環境及正負10%電壓變動下，皆能展現極高穩定性。如圖三所示，傳統自然起振需1.1毫秒，而開啟快速起振電路後僅需16.3微秒即可達穩態，達成約69倍起振加速。本技術在微秒級起振速度與極低能耗間取得卓越平衡，為下一代綠能物聯網晶片提供了創新的時脈解決方案。



圖一 電路系統架構圖。



圖二 快速起振之時序圖。

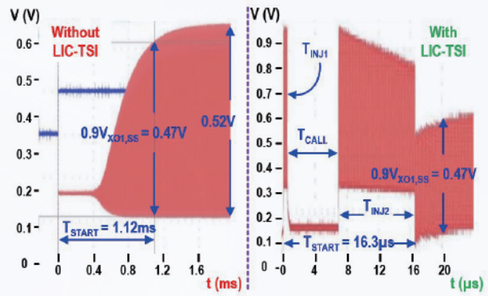
Abstract

In Internet of Things (IoT) and wireless communication systems, a stable and precise reference clock is indispensable. Among various options, the crystal oscillator (XO) is the premier choice for generating reference clocks due to its high quality factor and excellent temperature stability. However, its startup time is inherently long, often requiring several milliseconds to reach a steady state. Modern IoT devices extensively employ "duty cycling" to conserve power, spending the majority of their time in sleep mode, because battery replacement for these distributed nodes is often extremely difficult. During wake-up cycles, this prolonged startup time wastes a significant amount of battery energy. While prior energy injection techniques can accelerate this process, they are frequently accompanied by lengthy iterative calibration times and high hardware overhead.

To resolve this pain point, this work proposes a two-step energy injection architecture equipped with a Linear-Interpolation Injection calibration technique, and its system architecture is illustrated in Fig.1. The core circuit utilizes a digitally controlled ring oscillator (DCO) to assist in generating the injection energy. Upon startup, a brief first energy injection is initially performed. Subsequently, the system automatically and rapidly measures the frequency error between the DCO and the crystal under the highest and lowest DCO frequency tuning settings. Because the relationship between the DCO's period and its control capacitance is approximately linear, the system avoids time-consuming blind guessing. Instead, it utilizes a linear interpolation mathematical formula to directly calculate the accurate DCO control signal within constant time, aligning the DCO frequency perfectly with the crystal's 40 MHz and completely eliminating the latency of traditional step-by-step tracking. Following this, the system uses this calibrated frequency to perform a second, powerful energy injection to rapidly wake up the crystal, where the overall timing sequence of the fast-startup process is shown in Fig.2.

In terms of industry applications, this technology is highly compatible with wearable devices, medical sensors, Bluetooth trackers, and smart home nodes. These devices remain in sleep mode for the vast majority of their operational time. Compressing the preparation time during frequent wake-ups from the millisecond scale down to the microsecond scale can significantly extend device battery life from months to several years, and significantly reduce corporate maintenance costs.

This chip is fabricated using the TSMC 90-nm CMOS process, with a measured average power consumption of only 70 microwatts. It demonstrates exceptionally high stability across a wide temperature range from -40° C to 125° C and under ±10% voltage variations. As illustrated in Fig.3, conventional natural startup requires 1.1 milliseconds. In contrast, reaching a steady state takes only 16.3 microseconds after enabling the fast-startup circuit, achieving an approximately 69x startup acceleration. This technology achieves an outstanding balance between microsecond-level startup speed and ultra-low energy consumption, providing an innovative clock solution for next-generation green IoT chips.



Without LIC-TSI	With LIC-TSI			
T_{START}	T_{INJ1}	T_{CALI}	T_{INJ2}	T_{START}
1.12ms	0.5µs	6.2µs	9.6µs	16.3µs

Fig. 3 Measured startup waveforms without and with the proposed LIC-TSI technique.