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Frequency measurement and analysis via different frequency phase synchronization fuzzy region

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Abstract: A precise frequency measurement and analysis method utilizing the concept of the different frequency phase synchronization fuzzy region is presented based on the principle of phase synchronization detection. Initially, the frequency of the measured signal was roughly estimated by using the traditional high-precision time and frequency detection technology. Subsequently, the frequency estimated was fed into a direct digital synthesizer (DDS) to generate a real-time frequency standard signal that exhibited a slight frequency deviation relative to the measured signal. The edge pulses of the different frequency phase synchronization fuzzy region served as counter switch signals, enabling the counting of both the detected signal and the real-time frequency standard signal within a specified gate time. Through subsequent data processing of the obtained values, the frequency, frequency difference, and frequency accuracy of the detected signal could be determined. Experimental results demonstrate that the system based on this method achieves a frequency stability of 10^{-13} at 1 s, with a frequency deviation of less than 3 Hz. Compared with traditional frequency measurement and analysis methods, this approach has many advantages, especially its fast response time of less than 1 ms, high measurement accuracy of more than 10^{-11} at 1 s, high integration with only one FPGA chip, and cost of less than 1 000 yuan. It is widely applied in the fields of time and frequency services and security technology of the Beidou satellite (BDS) navigation system, such as BDS pseudo-range measurement, Beidou positioning, navigation and time services, as well as precise time and frequency measurement and control, etc.

Key words: different frequency phase synchronization; frequency analysis and measurement; frequency accuracy; phase synchronization fuzzy region; frequency stability; group period

0 Introduction

Frequency analysis and detection are a critical focus in precision physical parameters metrology and Beidou satellite (BDS) positioning, navigation, and timing. It plays a pivotal role in time synchronization, phase noise characterization, atomic frequency standard evaluation, frequency base development, frequency standard research, and performance testing. Frequency measurement techniques have found extensive applications across various domains including electronic engineering, measurement and testing, instruments and meters, communication, and radar detection. The demand for enhanced frequency stability has been steadily increasing. Frequency stability serves as a key technical metric in frequency measurement and is the primary criterion for assessing the quality of precise frequency sources. Evaluating the stability of the frequency for a frequency source through frequency measurement remains the most effective approach[1-2]. Currently, the predominant methods for frequency measurement include the pulse counting, differential frequency multiplication, direct beat measurement, and phase detection techniques.

The pulse counting method employs a counter to assess the stability of a frequency source. Direct measurement with a standard counter typically yields frequency stability results on the order of 10^{-7}, which falls short of the precision required for modern frequency standards[3]. Ryszard et al.[4] utilized pulse frequency measurement in conjunction with FPGA technology to achieve a frequency uncertainty less than 56 ps within the 11.5 ns time range. In terms of engineering applications, given the limitations of the pulse counting method, differential frequency multiplication techniques are usually employed to enhance accuracy. The differential frequency multiplication involves amplifying the frequency difference of the detected signal using a multiplier and then measurement this amplified difference with a high-resolution counter[5]. Ryu et al.[6] used a locking-ring clock

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generator to develop a frequency multiplier clock, spanning the output frequency range from 100 MHz to 3.3 GHz. This method is straightforward, reliable, and well-suited for high-precision frequency standards. Nevertheless, because of the ± 1 count error and the impact of multiplication-induced noise, the highest achievable measurement accuracy remains at the 10^{-10} level.

The direct beat method involves directly mixing two comparison signals using a low-noise mixer[7]. Using a high-precision counter to measure the generated beat frequency signal enables the precise measurement of the frequency accuracy. Liu et al.[8] proposed a digital beat method system that employed a beat analyzer instead of counter. While the stability of the analog beat signal equals to 4.7×10^{-12} at 1 s, the stability of the digital beat signal improves to 3×10^{-14} at 1 s. In addition to offering high precision and resolution in frequency stability measurements, this method also supports broadband frequency stability measurements, extending up to 18 GHz. The direct temperature measurement system can be used to measure the frequency stability of microwave signals with high precision. A representative instrument for this purpose is the frequency stability analyzer HP5390A, which incorporates a clock frequency counter with 500 MHz and can measure the stability of the frequency as low as 10^{-13} at 1 s within the range of 500 kHz to 18 GHz. The phase comparison method assesses the frequency stability of a frequency standard by measuring the temporal phase changes of the signal. Yang et al. utilized this technique to achieve an accuracy of 10^{-13} at 1 s in frequency standard comparisons[9-11]. This method offers high resolution, particularly for comparing two signals with identical frequencies. However, when comparing signals of different frequencies, the process becomes more complex as it requires frequency conversion through mixers components to lead to the normalization of frequency. This not only increases the cost of the equipment but also introduces additional noise from the circuitry, thereby limiting its broader application[12-13]. Moreover, at higher frequencies, the method cannot generate square wave signals with sharp leading and trailing edges, resulting in delays to the input signal. Consequently, dead zone and nonlinear phenomena occur, which become more pronounced as the comparison frequency increases.

In summary, conventional frequency measurement instruments face inherent trade-offs when evaluating the performance metrics of diverse signal sources: achieving high measurement accuracy while maintaining cost-effectiveness and structural simplicity remains challenging. Traditional approaches rely on multi-stage frequency conversion techniques—including mixing, division, and multiplication—which introduce cumulative systematic uncertainties[14-17]. To address these limitations, we propose a novel high-precision frequency measurement method grounded in the concept of different-frequency phase-synchronization fuzzy regions.

1 Frequency measurement principle

The traditional method of frequency measurement relies on frequency comparison signals, specifically frequency normalization, which does not permit direct phase comparison between different frequency measurement signals. In the actual process of handling and comparing signals, the nominal frequency values between the frequency standard and detected signals often differ due to factors such as noise from the detection device, external environmental factors, and the specific application of frequency measurement in various domains. When comparing the phases of different frequency signals based on their periods, phase comparisons lack continuity and synchronization. However, when group periods are used as time intervals, phase comparison exhibits strict consistency[18].

The frequency relationship between the two comparison signals is directly reflected through the group period. When the frequency relationship becomes very simple, the frequencies nominal values maintain a strict integer multiple, the group period corresponds to the least common multiple (LCM) of these periods, and the phase difference remains strictly synchronized with this LCM period. In cases where there is a slight relative frequency deviation between the two signals, such that the nominal frequencies do not maintain a strict integer multiple, the phase difference becomes continuous over the group period intervals, forming a regular phase coincidence fuzzy region[19]. For more complex frequency relationships, including significant frequency differences, it becomes challenging to generate phase synchronization points between the detected and frequency standard signals, the phase synchronization fuzzy regions and its changes in the time intervals between these regions become irregular[20-21]. During the phase comparison process based on group periods, the presence of the fuzzy regions is unavoidable. Given that the resolution of the phase measurement detectable during different frequency phase comparison often exceeds the resolution of the phase detecting device, all phase differences smaller than the detection threshold of the detecting device are not identified. As a result, the detecting device has the same outputs for these

unidentified phase comparison results, thereby forming the different frequency phase synchronization fuzzy region, or simply, the fuzzy region, as illustrated in Fig.1.

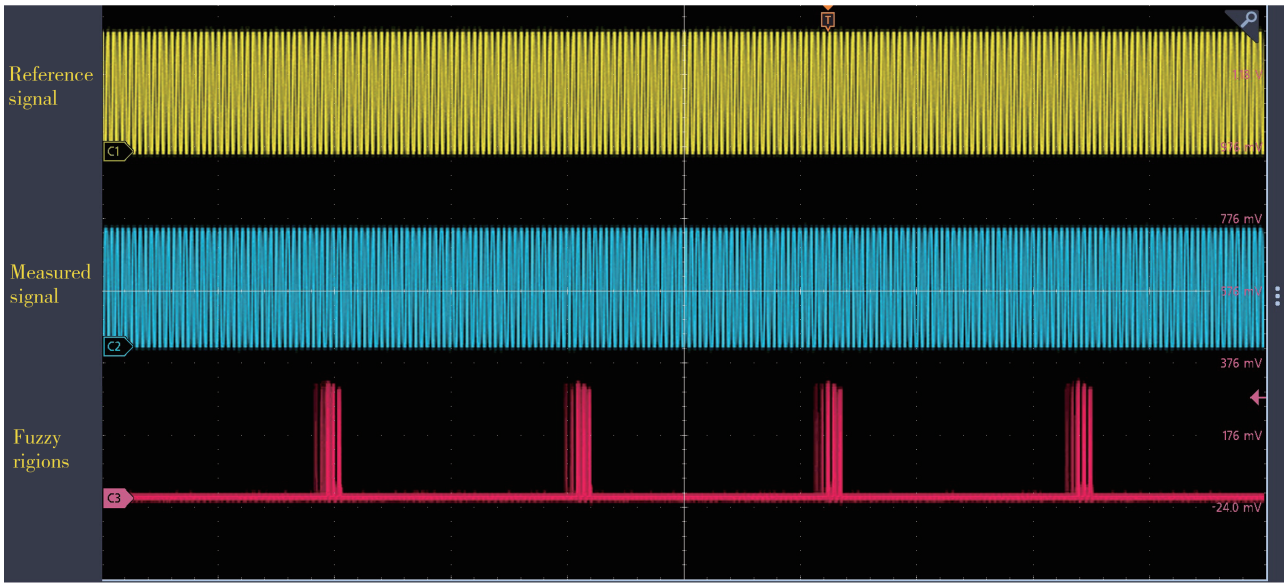


Fig. 1 Phase synchronization fuzzy regions.

In practice, the fuzzy region consists of a cluster of phase synchronization pulses that are undetectable by the detection circuit, encompassing all phase synchronization pulses with varying degrees of phase synchronization below the detection threshold, leading to nearly identical outputs.

The accuracy of frequency measurement depends on the stability of the edge of the fuzzy area. The phase synchronization pulse located exactly in the middle of the fuzzy area represents the maximum phase synchronization degree or the minimum phase difference between the detection signal and the frequency standard signal, and is also known as the optimal phase synchronization pulse. When the phase synchronization pulse is used as the switch of the counter gate controller in the actual phase comparison system, its implementation is quite challenging. In reality, the counter gate's switch is usually derived from the fuzzy region's edge pulses. The stability of these edge pulses directly influences the precision of phase comparison. Generally, the frequency measurement's accuracy is determined by the phase detecting device's resolution, which typically reaches an order of 10^{-9}. However, by utilizing the fuzzy region's edge pulses as the counter gate's switch and leveraging their stability to detect the counter gate's time interval, the accuracy of frequency measurement can surpass 10^{-12}. The factors influencing the edge pulse's stability in the fuzzy region stem from two primary sources: the stability and resolution of the detection device, and the uncertainty of the frequency relationship between the detected and frequency standard signals.

Typically, the phase synchronization detection device exhibits high resolution stability, while the frequency relationship between the detected and frequency standard signals predominantly determines the fuzzy region edge pulse's stability. The variation range of the fuzzy region edge pulses or width is contingent upon the detection device's resolution. When the frequency relationship between the detected and frequency standard signals is constant or exhibits a small difference of frequency, the change of the fuzzy region edge pulses mirrors that of the gate switch of the counter, leading to consistent errors. That is to say, using the two fuzzy regions' edge pulses as switching signals for the counter to open and close the gate at the same point within the group period introduces quantization errors. However, since these errors are consistent, a high measurement precision of gate time can still be achieved. When the frequency relationship between the detected and frequency standard signals becomes very simple, multiple regular serial fuzzy regions form at intervals of the LCM period. With the small frequency differences between the measured and frequency standard signals, multiple regular serial fuzzy regions form at intervals of the group period. For very complex frequency relationships, the more fuzzy regions can be achieved through delayed technology. The generation of fuzzy regions and their edge pulses is illustrated in Fig.2.

In Fig. 2, the frequency standard signal f_0 equals to 5 MHz, the detected signal f_x equals to 5.1 MHz. The $f_{\max c}$ between them equals to 0.1 MHz. The

corresponding maximum common period T_c represents the measurement resolution.

$$T_c = \frac{f_{max\,c}}{f_0 f_x} = \frac{0.1}{50 \times 51} \approx 39.2\ \text{ps}. \tag{1}$$

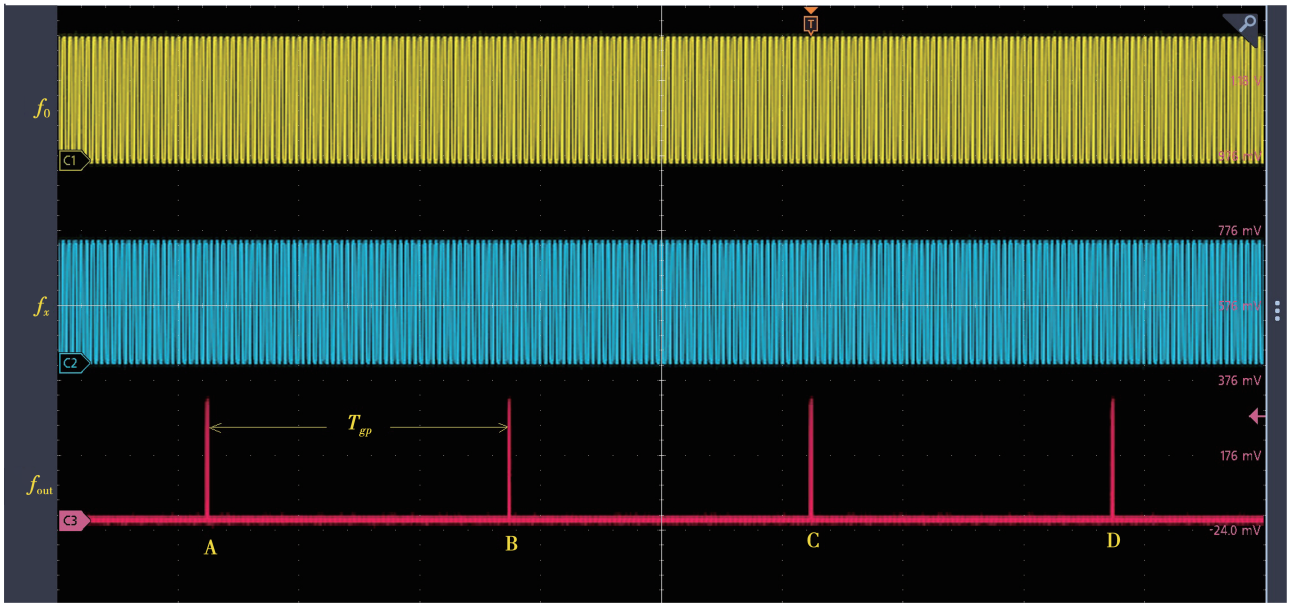


Fig. 2 Fuzzy regions pulses generation

From the fundamental principles of phase synchronization at different frequency frequencies, the smallest phase difference within a group corresponds to the measurement resolution, while other phase differences are integer multiples thereof. Consequently, any phase differences below the resolution threshold of the phase synchronization detecting device cannot be discerned in the phase comparison results, leading to ambiguous regions (e.g., A, B, C, D). The time lengths among these fuzzy regions edges are defined as

$$T_{gp} = \frac{1}{f_{max\,c}} = 10\ \mu\text{s}.$$

Given that the two signals of phase comparison exhibit a small difference of frequency, the fuzzy regions remain constant. Each phase difference will be strictly synchronized within the group cycle, and this phenomenon is called phase group synchronization. Therefore, different frequency phase comparison demonstrates continuity based on the T_{gp} synchronization, with the T_{gp} serving as the interval.

2 Frequency measurement scheme

Through the analysis of fundamental principles of frequency measurement, a precise frequency measurement scheme utilizing the different frequency phase synchronization fuzzy region has been designed, as illustrated in Fig.3.

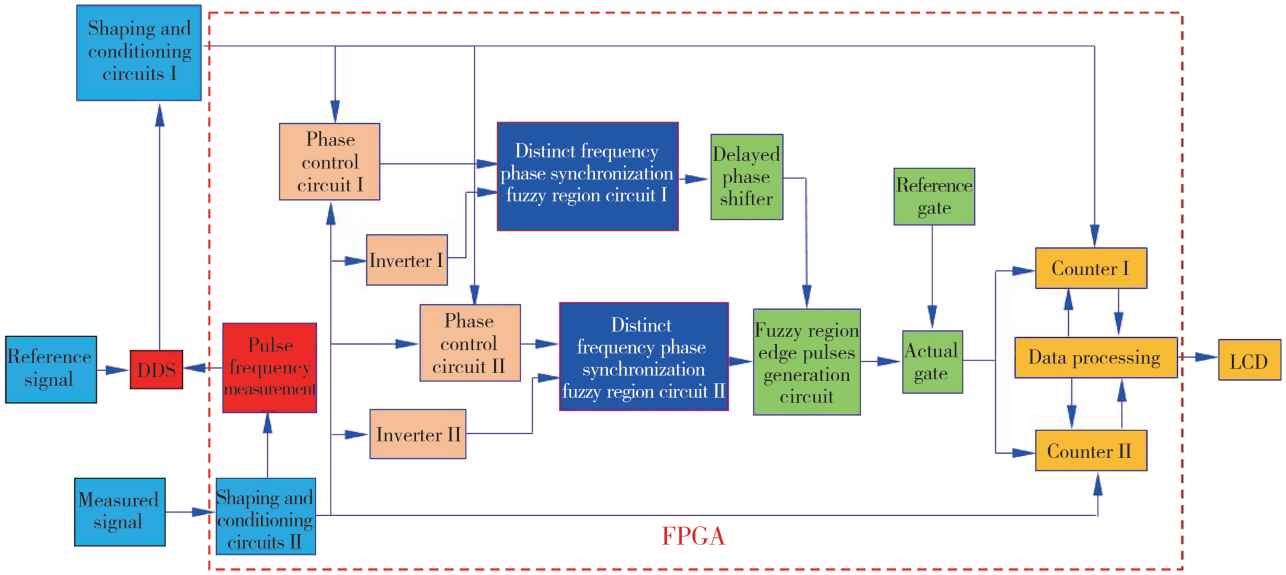


Fig. 3 Frequency measurement scheme based on different frequency phase synchronization fuzzy region

This scheme comprises a direct digital synthesis (DDS) frequency synthesis circuit, a signal conditioning and shaping circuit, a different frequency phase synchronization fuzzy region circuit, a counter gate generation circuit, data processing circuit, and LCD output circuit. The design of frequency measurement system is primarily implemented using FPGA technology. Initially, the detected and frequency standard signals undergo conditioning and shaping processes. Shaping converts the comparison signal into a digital pulse signal, while conditioning adjusts this digital pulse signal to match the appropriate pulse width and achieve phase synchronization. Subsequently, the detected frequency is estimated and this estimate is transmitted to the DDS synthesizer. A communication protocol is established between the FPGA and the DDS to ensure that the DDS can interpret the FPGA, such as frequency estimate values from the FPGA. These estimates are converted into relevant frequency words through the DDS. By this protocol, the frequency word instructs the DDS to generate a real-time frequency standard signal with a frequency estimate value matching that of the measured signal. Next, the measured signal is detected alongside the real-time frequency standard signal and its delayed phase-shifted counterpart to generate the different frequency phase synchronization fuzzy region. This fuzzy region is then fed into the generation circuit of the edge pulses to get the fuzzy region's edge pulses. Finally, within the time interval controlled by the reference gate, the fuzzy region's edge pulses serve as the counter's gate switching. The measured signal and the real-time frequency standard signal are counted, and the calculated value is obtained. Through data processing of this calculated value, the frequency, frequency difference, and stability of frequency for the detected signal are accurately determined.

2.1 Pulses generation and conversion circuit

The fuzzy region's edge pulses serve as the switching signal for the actual counter gate, produced by the fuzzy zone edge pulses detection device. This device is a phase synchronization detection device composed of an AND logic gate circuit. To trigger the counter gate, the pulse widths of both the detected and frequency standard signals should meet the requirements for generating a phase synchronization pulse level. Consequently, it is essential to minimize the pulse signals' width of the detected and frequency standard signals. The pulse widths of these signals significantly influence the detection accuracy of the entire frequency detecting system. From the phase synchronization detecting principle, the phase synchronization pulse's width is determined by the narrowest pulse along the two comparison signals' rising edge. However, due to the limitations in the detection sensitivity of the detecting device, i.e., the detecting resolution of the detecting device, the pulse width of the rising edge of the synchronization signals cannot be infinitely narrow. Therefore, adjusting the measured and frequency standard signals' pulse widths to an appropriate width triggering the actual counter gate is necessary to enhance the system's frequency detecting accuracy, as illustrated in Fig.4.

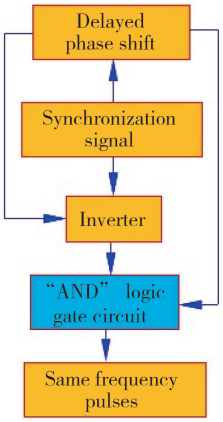


Fig. 4 Pulse generating circuit with identical frequency features an appropriate pulse width

The detected and frequency standard signals' pulse widths are adjusted using a delay phase-shifting circuit such as the clock of an edge-triggered D flip-flop. When the width of the pulse is adjusted to the point where the detected signal's frequency value can no longer be identified by the detecting system, this pulse width represents the optimal synchronization signal width, which can enhance the measuring resolution and accuracy, as illustrated in Fig.5.

2.2 Real-time frequency standard signal generation circuit

To ensure a smaller frequency difference between the detected and frequency standard signals, a real-time frequency standard frequency tracking circuit was designed. This circuit achieved time and phase synchronization or constancy for each phase difference within group period intervals during the phase synchronization process. As illustrated in Fig.3, the fuzzy regions are highly centralized and exhibit serial law with group period intervals. From Fig.2, $f_x = Af_{\max c}$ represents the frequency of the detected signal, corresponding period T_x, while $f_0 = Bf_{\max c}$ denotes the frequency of the frequency standard signal, corresponding period T_0. The beat frequency between the detected and frequency standard signals is $f_{\max c}$, A and B $(B < A)$ are integers greater than zero, respectively.

$T_{\min c}=1/f_{\max c}$ represents the beat period between the detected and frequency standard signals. The relative frequency difference value between the detected and frequency standard signals Δf indicates that the actual frequency of the frequency standard signal is $f_{0a}=f_0\pm\Delta f$, leading to the time drift Δt, which means the actual period of the frequency standard signal is $T_{0a}=T_0\mp\Delta t$.

Due to the Δf, the changes of phase difference over the $T_{\min c}$ lead to the formation of group periods T_{gp}. Each group period T_{gp} encompasses several $T_{\min c}$, ensuring phase synchronization at group intervals rather than at the $T_{\min c}$. Within a group period T_{gp}, the changes of phase difference in the nth period (n is the number of the $T_{\min c}$ in group period T_{gp}) are

$$\begin{bmatrix}\Delta P_1^M\\ \Delta P_2^M\\ \Delta P_3^M\\ \vdots\\ \Delta P_B^M\end{bmatrix}=\begin{bmatrix}T_x[A(M-1)+M_1]-T_{0a}[1+B(M-1)]\\ T_x[A(M-1)+M_2]-T_{0a}[2+B(M-1)]\\ T_x[A(M-1)+M_3]-T_{0a}[3+B(M-1)]\\ \vdots\\ T_x[A(M-1)+A]-T_{0a}[B+B(M-1)]\end{bmatrix}=$$

$$\begin{bmatrix}T_x[A(M-1)+M_1]-[1+B(M-1)](T_0\mp\Delta t)\\ T_x[A(M-1)+M_2]-[2+B(M-1)](T_0\mp\Delta t)\\ T_x[A(M-1)+M_3]-[3+B(M-1)](T_0\mp\Delta t)\\ \vdots\\ T_xAM-(T_0\mp\Delta t)BM\end{bmatrix}=\begin{bmatrix}T_x[A(M-1)+M_1]-[1+B(M-1)](T_0\mp\Delta t)\\ T_x[A(M-1)+M_2]-[2+B(M-1)](T_0\mp\Delta t)\\ T_x[A(M-1)+M_3]-[3+B(M-1)](T_0\mp\Delta t)\\ \vdots\\ \pm BM\Delta t\end{bmatrix}. \tag{2}$$

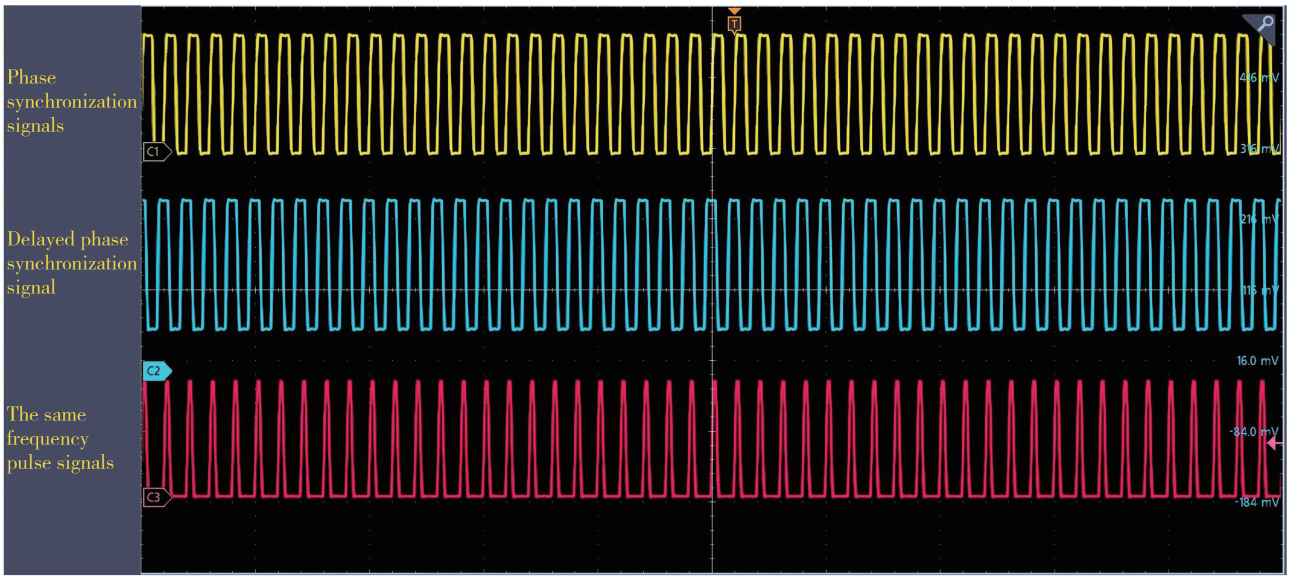


Fig. 5 Results of pulses generation and conversion

The phase difference's change value at adjacent $T_{\min c}$ is

$$|\Delta P_B^M-\Delta P_B^{M-1}|=BM\Delta t-B(M-1)\Delta t=B\Delta t. \tag{3}$$

The phase difference's change at the nth $T_{\min c}$ is $M\Delta p$. When the value of $M\Delta p$ changes to the maximum that is the detected frequency signal's period, there is

$$BM\Delta t=T_x. \tag{4}$$

At the moment when the phase difference at point $T_{\min c}$ begins to change periodically, it coincides exactly with the time when T_{gp} is generated as shown in Fig.3, that is

$$T_{gp}=MT_{\min c}\mp BM\Delta t. \tag{5}$$

According to Eq. (3), we can obtain

$$\left|\Delta P_B^M-\Delta P_B^{M-1}\right|=|AT_x-BT_{0a}|=\left|A\frac{1}{f_x}-B\frac{1}{f_{0a}}\right|=$$

$$\left|A\frac{1}{f_x}-B\frac{1}{f_0\pm\Delta f}\right|=\left|A\frac{1}{Af_{\max c}}-B\frac{1}{Bf_{\max c}\pm\Delta f}\right|=$$

$$\frac{\Delta f}{f_{\max c}(\Delta f\pm Bf_{\max c})}=\frac{\Delta f}{\Delta f\pm Bf_{\max c}}T_{\min c}. \tag{6}$$

Due to Eqs. (4) and (6), there is

$$T_{gp}=MT_{\min c}\mp BM\Delta t=T_x\frac{T_{\min c}}{\Delta tB}\mp T_x\frac{\Delta p}{\Delta tB}=T_x\mp$$

$$T_x\frac{T_{\min c}}{\Delta tB}=\frac{1}{f_x}\mp\frac{1}{\Delta tBf_x}T_{\min c}=\frac{1}{Af_{\max c}}\mp$$

$$\frac{1}{Af_{\max c}\Delta tB}T_{\min c}=\frac{1}{Af_{\max c}}\left(1\mp\frac{1}{\Delta tB}T_{\min c}\right)=$$

$$\frac{1}{Af_{\max c}}\left(1\mp\frac{Bf_{\max c}\pm\Delta f}{\Delta f}\right). \tag{7}$$

When $A=B$, that is, the nominal frequencies of the detected and frequency standard signals are the consistent, then

$$\Delta f=\frac{1}{T_{gp}}. \tag{8}$$

It follows that the T_{gp} is the reciprocal of the relative frequency deviation Δf. By using the fuzzy region's edge pulses as the counter's switch and considering the group period T_{gp} as the gate time, the real-time Δf between the detected and frequency standard signals can be accurately calculated, thereby obtaining the detected signal's frequency stability. The real-time frequency standard signal, synchronized with the detected signal, is generated by the real-time frequency standard tracking circuit, resulting in a minimal Δf between the detected and frequency standard signals, which adheres to Eq. (8). The detailed implementation scheme is illustrated in Fig.6.

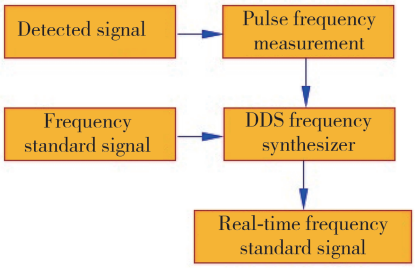


Fig. 6 Real-time frequency standard signal tracking circuit

In Fig.6, the control signal for the real-time frequency standard signal tracking circuit is derived using the pulse counting frequency detecting method to estimate the value of the frequency. Initially, the phase-locked loop within the FPGA doubles the 50 MHz system clock to the higher frequency clock, which subsequently produces the counter's gate via frequency divider. This counter's gate is then transformed into narrow pulse from rectangular pulse through pulse transform device to establish the actual counter gate, as illustrated in Fig.7.

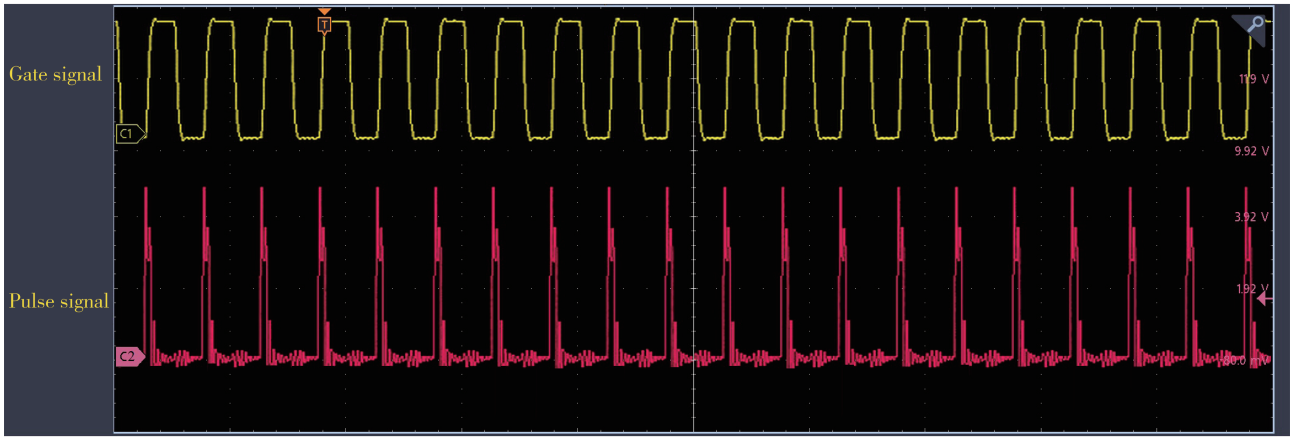


Fig. 7 Actual gate pulse signal conversion

Subsequently, the detected signal is input into the counter, where it is continuously counted within the gate to get a count value. The obtained count values are processed by the data processing circuit, thereby deriving an estimate of the detected signal frequency. The estimated frequency, serving as controlling DDS, matches the real-time frequency standard signal. Therefore, the estimated frequency of the detected signal corresponds to the frequency value of the real-time frequency standard signal. When the detected frequency changes, the frequency of the real-time frequency standard signal also changes accordingly, ensuring that the real-time frequency standard signal tracks the frequency estimate of the detected signal and maintains strict consistency. After getting the frequency estimate of the real-time frequency standard signal, which is equivalent to the detected signal, the real-time frequency standard signal must be produced to synchronize its phase with the detected signal. First, from the FPGA to DDS, communicating protocol needs to be established, and the estimated frequency is transmitted to the FPGA. The estimated frequency value is then converted into the corresponding frequency word using the DDS conversion algorithm of the frequency word. The frequency word controls the DDS's external clock to generate the real-time frequency standard signal. To enhance the real-time frequency standard signal's stability, a high stability signal source HU-800 is typically used as the DDS's external clock. In this case, the frequency conversion equipment is employed to generate a 1 ± 0.001 MHz signal, which is converted into pulse signal to serve as the detected signal. The FPGA controls the DDS frequency synthesizer, enabling it to generate a 1 MHz frequency standard signal as the external clock produced by the ultra-stable HU-800 crystal oscillator.

By tracking the frequency of the standard signal, the phase of any frequency signal within the radio frequency range can be directly processed, thereby avoiding the inherent limitations of phase synchronization methods with different frequencies. Specifically, it addresses the challenges of phase measurement, comparison, and processing under complex frequency relationships or significant frequency differences, effectively solving the phase synchronization problem under these conditions. This approach significantly broadens the range of the frequency detection, enabling arbitrary signals' frequency detection within the RF range while ensuring the frequency relationship's stability between the detected and frequency standard signals and maintaining detection resolution.

2.3 Phase synchronization fuzzy region generation circuit

When detecting the phase-synchronized ambiguous regions of different frequencies, if there is a simple frequency relationship between the detected signal and the frequency standard signal, that is, their frequencies are strictly integer multiples of each other, then there will be uncertainty in phase synchronization at the T_{minc}. However, in practical different frequency phase synchronization detection, the frequency relationship is often complex due to the Δf between the detected and frequency standard signals. This results in a phase drift rather than strict phase synchronization at the T_{minc}, leading to group periods. The complexity of the phase difference condition between the detected and frequency standard signals causes the phase synchronization fuzzy region to vary systematically over time. During different frequency phase synchronization, it is nearly impossible to utilize the optimal phase synchronization pulse as the counter gate's switch signal because its width is typically lower than the phase detection device's response time. During a T_{gp}, any phase differences that fall below the detection resolution threshold cannot be identified by the detection device. For these unidentifiable phase differences, the detection device outputs identical narrow pulses, which exhibit varying amplitudes due to differing degrees of phase synchronization, thereby forming the phase synchronization fuzzy region. If this fuzzy region is used as the counter gate's switch, the fuzzy region's edge pulse actually triggers the counter's gate. To ensure the effectiveness of the fuzzy region's edge pulses as trigger signals, the pulse widths of the two synchronization signals should be adjusted. Additionally, the real-time frequency standard frequency tracking should be employed to maintain the fuzzy region edge pulse's stability. To avoid measurement errors caused by the randomness of the edge pulses in the blurred area, it is usually necessary to extract the edges of the pulses, as shown in Fig.8.

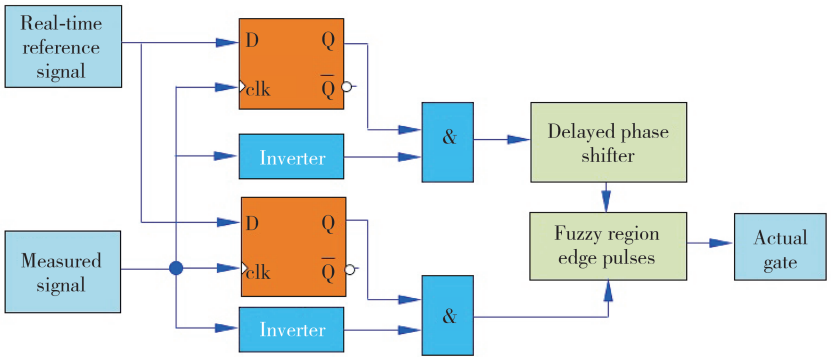


Fig. 8 Fuzzy regions edge pulses generation circuit for different frequency phase synchronization detection

In Fig.8, the fuzzy region edge pulses and fuzzy region itself are all produced by combinational logic and gate device. The response time of this logic gate device determines the detection resolution of the fuzzy region detection device, which is approximately at the nanosecond level (typically around 2 ns). Initially, the detected frequency signal and the real-time frequency standard signal are synchronized to detect phase differences within the group period that are less than 2 ns, thereby forming a fuzzy region. Subsequently, the detected signal undergoes a phase shift through delay, and the synchronization between the delayed detected signal and the real-time frequency standard signal is detected, resulting in a new fuzzy region. This new fuzzy region is temporally shifted relative to the original one, causing the edge pulses of the two regions to be desynchronized by approximately one delay unit. A smaller delay unit size, indicating finer delay phase shift resolution, results in a shorter interval time between the two fuzzy regions' edge pulses. The new fuzzy region's phase is then inverted and fed into the logic gate device along with the original fuzzy region to generate the fuzzy region's edge pulses. This edge pulse width is determined by the size of the delay unit. A narrower edge

pulse width corresponds to a reduced gate measuring error. Additionally, to confine the fuzzy region within the T_{gp}, a D flip-flop is employed as controlling phase to achieve the singularity of phase synchronization and minimize the fuzzy region's width. That is to say, the D input terminal of the edge-type D flip-flop is connected to the measured signal, while the clock terminal is connected to the frequency standard signal. This ensures that the phases of the two signals remain sequential before they phase-coincide. The phase of the frequency standard signal always remains ahead of that of the measured signal, and as a result, the width of the phase coincidence or the phase coincidence fuzzy region is reduced by half. For generating fuzzy region's edge pulses, these edge pulses primarily reflect the different frequency phase synchronization detection results between the detected and real-time frequency standard signals, both before and after the time delay.

The phase synchronization pulse results are illustrated in Fig.9.

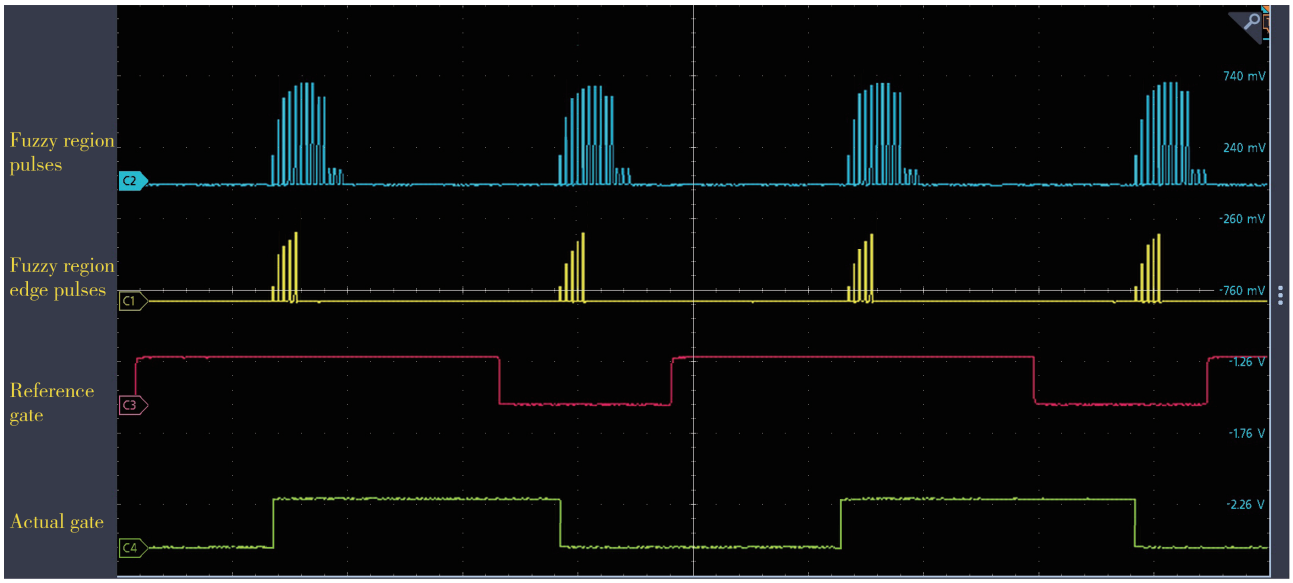


Fig. 9 Fuzzy region edge pulses generation

2.4 Measurement gate generating

The actual counter gate is produced by reference gate control, as illustrated in Fig.10.

If the fuzzy region's edge pulses are used directly as the counter's switching, the actual gate will become unstable due to the inherent unpredictability of the fuzzy region's edge pulses. Specifically, factors such as the random nature, irregular timing, and inconsistent intervals between these edge pulses can lead to significant quantization errors.

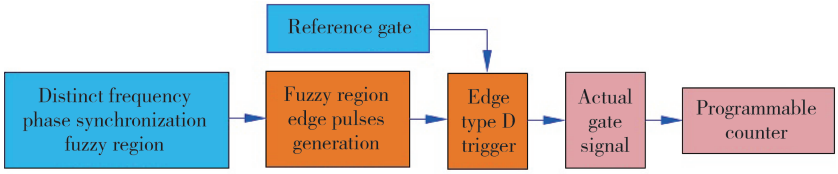


Fig. 10 Measurement gate generating circuit

First, a programmable divider is utilized to generate a reference gate signal with proper frequency, which is then transmitted to an edge-triggered D flip-flop's input. Subsequently, the fuzzy region's edge pulse serves as the D flip-flop's clock, and its output is directed to the programmable counter's enable terminal. Next, the reference gate's high-level and low-level pulses are collected as the opening and closing signals for the counter, respectively, thereby generating the actual counter gate. Finally, the detected and real-time frequency standard signal are counted within the actual gate to obtain the counting value, which is subsequently sent to the data processing circuit for calculating the frequency, frequency difference, and other parameters of the detected signal.

$$f_x = \frac{N_x}{N_0} f_{0a}. \tag{8}$$

where f_x represents the detected signal, N_x represents the detected signal's counting value, while N_0 denotes the counting value of the real-time frequency signal f_{0a} during the same period.

$$\sigma(\tau) = \sqrt{\frac{1}{2(N-1)} \sum_{i=0}^{N-1} \left(\frac{f_{i+1} - f_i}{f_x} \right)^2}, \tag{9}$$

where f_x is the detected frequency, i is the frequency

measurement's times, f_i is the measurement frequency of the ith time, f_{i+1} is the measurement frequency of the $(i+1)$th time, N is the groups number of taken measurements, τ is the time interval or time length of stability, and $\sigma(\tau)$ is Allan's variance. The testing results are illustrated in Fig.11.

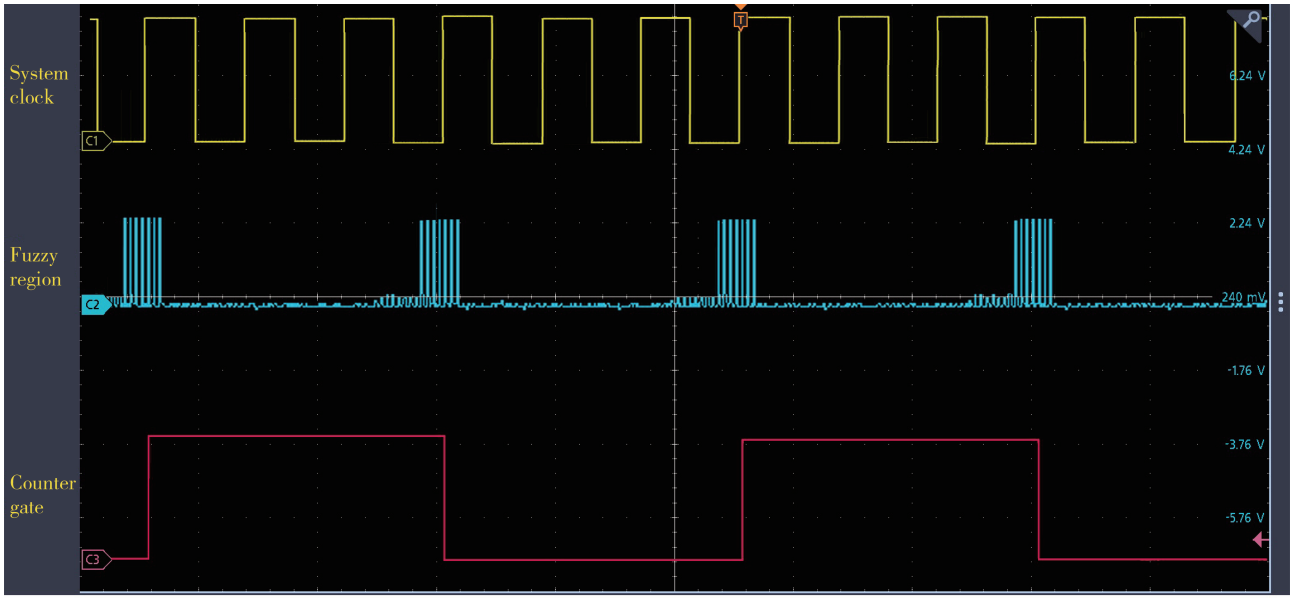


Fig. 11 Testing results of actual gate generation

Utilizing the signals from the fuzzy area to control the opening and closing of the opposite door has three significant advantages. First, the ± 1 word's measurement error in conventional frequency detection is avoided. Second, the fuzzy region signal's stability mitigates the jitter in measurement gate produced by the detecting device errors, thereby enhancing the gate measurement's precision. Third, it operates under the lower measuring resolution, thereby achieving higher frequency stability. Specifically, if the fuzzy region is stable enough, then when the variation range of the system's measurement resolution is lower than the detection resolution, it will only affect the width of the fuzzy regions, without affecting the accuracy of the gated measurement.

3 Results and discussion

Currently, a scheme of frequency measurement utilizing the different frequency phase synchronization fuzzy region has been developed. The frequency measurement range of this prototype device is the same as that of the pulse-counting type frequency detection device. The experiment can be conducted under ambient laboratory conditions (20—25 ℃). The prototype incorporates both an internal and an external frequency reference. The internal reference is a temperature-compensated crystal oscillator (TCXO), whereas the external reference is a high-performance cesium atomic clock. For enhanced measurement accuracy and long-term stability, the external frequency reference—characterized by a fractional frequency stability of 5×10^{-13} at 1 s is routinely employed in standard frequency metrology applications. Theoretically, the system supports frequency measurements up to 3 GHz. However, initial empirical validation has demonstrated reliable operation primarily within the 0—100 MHz range. The reason for this limitation is that at higher input frequencies, the phase relationship between the test signal and the reference signal becomes complex, thereby hindering the accurate identification of the phase coincidence points during the time-domain phase comparison process. Consequently, the synchronization criterion governing the phase-coincidence fuzzy zone becomes ambiguous, leading to degraded measurement accuracy and temporal stability. To address this, signals exceeding 100 MHz are typically down-converted—via harmonic mixing or prescaling—to an intermediate frequency near 100 MHz, thereby ensuring unambiguous establishment of the phase-coincidence fuzzy zone. This approach is grounded in a novel frequency measurement principle leveraging deterministic phase-coincidence detection, and the system's stability can reach the order of 10^{-13} at 1 s. In the frequency measurement process, a precise 5 MHz signal source HU-800 (with the stability of 5×10^{-13} at 1 s) is utilized to generate frequency standard signals. Meanwhile, a frequency synthesizer Agilent 8664A produces the detected frequencies, which are subsequently converted into narrow pulses matching the measured frequencies. The detection results for other frequencies are summarized in Table 1.

Table 1 Detection results of frequency

Detected frequency/Hz	Detection results/Hz	Frequency difference/Hz	Frequency stability/s
1 254 000	1 253 999.98	0.016	1.21×10^{-13}
8 326 000	8 326 000.02	0.022	2.15×10^{-13}
1 023 000	10 230 000.01	0.011	2.91×10^{-13}
16 384 000	16 383 999.97	0.024	2.23×10^{-13}
21 847 000	21 847 000.03	0.032	2.57×10^{-13}
28 637 000	28 637 000.02	0.021	3.72×10^{-13}
1 254 000	1 253 999.98	0.016	1.21×10^{-13}
32 785 000	32 784 999.97	0.022	3.01×10^{-13}
38 438 000	38 437 999.99	0.009	3.63×10^{-13}
40 758 000	40 758 000.18	0.184	3.47×10^{-13}
46 368 000	46 367 999.99	0.008	6.33×10^{-13}
52 684 000	52 683 999.91	0.093	6.24×10^{-13}
57 216 000	57 215 999.99	0.015	7.38×10^{-13}
66.375 000	66 374 999.92	0.850	8.17×10^{-13}
68 408 000	68 408 002.18	2.18	8.28×10^{-13}
77 387 000	75 386 999.91	0.093	8.42×10^{-13}
88 692 000	88 692 000.03	0.071	8.57×10^{-13}
93 512 000	93 512 000.14	0.137	8.48×10^{-13}

As illustrated in Table 1, the accuracy of frequency measurement can achieve up to 10^{-13} at 1 s, with a frequency deviation maintained below 3 Hz. While the accuracy slightly diminishes as the detected frequency increases, it remains within the order of 10^{-13} at 1 s even outside the 1—40 MHz range. This performance is primarily table attributed to three key factors. First, real-time frequency standard tracking technology significantly enhances the frequency relationship's stability between the detected and frequency standard signals. The high fuzzy region stability generated by the detected and frequency standard signals ensures high detecting precision, which relies more on stability than resolution. Second, the delay phase shift technique facilitates phase synchronization across different frequencies based on their mutual frequency relationship, thereby mitigating the frequency relationship's influence between the detected and frequency standard signals. On one hand, this technique actively acquires the phase synchronization fuzzy region rather than passively generating it, ensuring the accurate formation of the actual gate. On the other hand, it reduces or eliminates system errors caused by electromagnetic interference, detection noise, stray signals, and other factors affecting frequency stability, thus maintaining a stable measurement gate and ensuring smooth frequency measurement. In addition, minor fluctuations in the signal strength within a narrow range exert negligible influence on test outcomes. However, excessively high measured signal strength can induce waveform distortion during phase comparison. This distortion manifests as an irregular, non-synchronous overlap region between phases—commonly appearing as a blurred or indifferent boundary—which critically compromises both the accuracy and stability of the measurement. Third, under the condition of stable gate measurement, the delay time technology preserves the frequency relationship between the detected and frequency standard signals, enhancing the measuring resolution while ensuring high accuracy and stability. From above analysis, compared with the most widely used commercial frequency measurement instruments, the proposed method exhibits short-term frequency stability and accuracy that are marginally lower than those of the double mixing time difference (DMTD) technique and the K+K FXE phase-based frequency counter.

However, these high-precision reference instruments feature significantly more complex architectures and larger physical footprints, resulting in substantially higher procurement and operational costs. In contrast, the proposed approach achieves markedly improved measurement consistency, a simpler implementation architecture, lower hardware cost, broader applicability across diverse operational scenarios, and greater potential to satisfy stringent precision requirements under varying environmental conditions. Importantly, this method is specifically designed for evaluating short-term frequency stability—or equivalently, short-term precision—of frequency signal sources, rather than long-term stability, which is not its primary performance objective. Furthermore, although ambient environmental factors may theoretically affect the stable frequency relationship between synchronized signals, the real-time tracking capability of the adopted frequency standard effectively mitigates or eliminates any appreciable degradation in the stability of the synchronous frequency source.

4 Conclusions

This paper introduces an innovative frequency detection method utilizing phase group synchronization in a fuzzy region for different frequencies. Real-time frequency standard signal tracking ensures the frequency relationship's stability between the detected and frequency standard signals during the process of phase synchronization across varying frequencies, including complex and large frequency differences. The proposed frequency measurement method is applicable across both low- and high-frequency regimes, with a theoretical upper limit of 3 GHz. However, at extremely high frequencies—particularly beyond several gigahertz—the increasingly complex nonlinear relationship

between the measured signal and the reference frequency impedes the unambiguous identification of phase coincidence zones. In the absence of a stable synchronization pattern, this leads to degraded frequency stability and measurement accuracy, and may ultimately result in measurement failure. To mitigate these limitations, frequencies above 1 GHz are typically down-converted to an intermediate frequency near 100 MHz using a harmonic mixer or frequency translator prior to measurement. This preprocessing step preserves both wide dynamic range and high metrological fidelity. The real-time synchronization enhances the phase resolution's stability between the detected and frequency standard signals. The fuzzy region's edge pulses which depend on the circuit's detection resolution are also notably stable and reliable.

Consequently, the frequency detection's accuracy relies more on this stability rather than on resolution alone. Thus, higher frequency measurement or phase synchronization accuracy can be achieved with relatively low measurement resolution, reducing system design complexity and development costs while enhancing system reliability and robustness. Additionally, to accelerate frequency measurement speed, the delay time technology is employed. This technology ensures that the fuzzy region' edge pulses are produced actively even under a very complex physical environment or frequency relationships, thereby guaranteeing the counter gate's accuracy. Experimental findings demonstrate that within the frequency range of 1—40 MHz, the new frequency detection method achieves a frequency measurement accuracy of 1.21×10^{-13} at 1 s. Compared to conventional frequency detecting method, the proposed method not only offers high precision but also exhibits superior reliability and stability, making it highly promising for applications in Doppler velocity measurement and ranging, BDS positioning, navigation and timing, precision time-frequency measurement and control, metrology, radar, and communication.

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Declaration of conflicting interests

The authors have no conflicts of interest related to this publication.

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基于异频相位同步模糊区的频率测量和分析

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摘　要： 基于相位同步检测原理，本文提出了一种利用异频相位同步模糊区域概念的精密频率测量和分析方法。首先，利用传统高精度时间和频率检测技术对被测信号的频率进行粗略估计。其次，将该估计频率输入到直接数字合成器（DDS）中，生成一个与被测信号略有频率偏差的实时频率标准信号。异频相位同步模糊区域的边沿脉冲作为计数器的开关信号，能够在指定的门控时间内对被测信号和实时频率标准信号进行计数。通过对所获得的计数值进行后续数据处理，可以确定被测信号的频率、频率差和频率精度。实验结果表明，基于此方法的系统实现了10^{-13}/s的频率稳定度，频率偏差小于3 Hz。与传统的频率测量和分析方法相比，这种方法具有诸多优势，尤其是其响应时间小于1 ms时，测量精度高达10^{-11}/s，且集成度高，仅需一个成本低于1 000元人民币的FPGA芯片即可完成系统设计。因此，它在北斗时频服务与安全技术领域（如北斗伪距测量、北斗定位、导航和授时以及精密时间频率测量和控制）等方面具有广泛的应用。

关键词： 异频相位同步；频率分析和测量；频率准确度；相位同步模糊区；频率稳定度；群周期

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