International Journal of Control and Automation
Vol. 9, No. 7 (2016), pp.385-396
http//dx.doi.org/10.14257/ijca.2016.9.7.36

Improvement of Rubidium Clock's Frequency-temperature Characteristic

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Abstract

The improvement of the widely used rubidium clock's frequency-temperature characteristic is an important topic of research. Through the research of the working principle of the rubidium clock and the frequency-temperature characteristic of it, we put forward a kind of scheme based on frequency compensation technique, including realization circuit, signal processing method and optimal control method for frequency conversion process. By applying the scheme, a commercial rubidium clock frequency-temperature characteristic has been improved dramatically without a deterioration of the clock's other performance parameters. Compared with the traditional one, the method proposed has some advantages such as easy realization, high stability, high precision, easy adjustment etc.

***Keywords**: atomic clock; satellite-borne atomic clock; frequency-temperature characteristic; frequency changed compensation technical*

1. Introduction

The passive rubidium atomic clocks take important roles in popular use at present. They are similar in structure, which are mainly comprised of physical body, local oscillator, frequency conversion circuit and servo circuit. They have almost the same working principle, operating by disciplining a crystal oscillator to the hyperfine transition at about 6.834 GHz in rubidium. The amount of light from a rubidium discharge lamp reaching a photo detector through a resonance cell will drop by about 0.1% when the rubidium vapor in the resonance cell is exposed to microwave power near the transition frequency [1]. The crystal oscillator is stabilized to the rubidium transition by detecting the light dip while sweeping an RF frequency synthesizer (referenced to the crystal) through the transition frequency. The compact rubidium clock, for its advantages in size, weight, energy consumption, price and flexibility to terrible environment, as well as its satisfaction to most practical requirements, is widely used in communication, electronic instrumentation, positioning, power generation, invisible target detection, observation control, measurement and other national economy and national defense fields. At the current market of the atomic frequency standard, the compact rubidium clock occupies 95% of the market share. Therefore, the development of the compact rubidium clock deserves people's attention. Frequency-temperature characteristic is one of the factors that influence long-term stability of frequency. How to improve the frequency-temperature characteristic of the abovementioned atomic clock is an important research topic. At present, the improvement of frequency-temperature characteristic is realized by optimal temperature control design and physical design [2]. A double-layer temperature-control circuit is adopted, with a reasonable gradient of temperature designed according to the distance between the two layers [3]. But the debugging of a double-layer temperature-control circuit is very troublesome. Besides, experiments have revealed that

ISSN: 2005-4297 IJCA

if the temperature of the certain parts gradually rises with the lapse of time, the temperature control of the two layers may present remarkable fluctuation of the temperature. Optimal design of the physical part in accordance with frequency-temperature generation principle is another widely used method in improving the frequency-temperature characteristic. However, this method requires lots of theoretical calculation and high level of manufacturing technique. This paper has proposed a method improving rubidium clock’s frequency-temperature characteristic based on compensation technique. The efficiency of the method is illustrated by an analysis and an experiment result.

2. Principle

The atomic resonance that forms the basis of the Rb clock's operation is the transition between two hyperfine states of 87Rb. The ground state of Rb is split into two hyperfine levels by the magnetic-dipole interaction between the single valence electron and the nucleus. Those states are labeled by the total-angular-momentum quantum number F. Each hyperfine state is further split into Zeeman sublevels, characterized by the quantum number mF. The mF=0 sublevels are unaffected to first order by stray magnetic fields, which can arise in devices from a host of internal and environmental sources. The so called 0-0 transition between the F = 2, mF = 0 and F = 1,mF = 0 states, with frequency f ≈ 6.834 GHz, is unaffected by such fields and is ideal for stabilizing[4]. The functional block diagram of the rubidium atomic clock we designed is shown in Figure 1 and the physics body of it is shown in Figure 2. The first step is to multiply the output of a voltage controlled oven controlled crystal oscillator (VCOCXO) by a PLL circuit to create a microwave field with a frequency near 6.834GHz. The microwave field is frequency modulated, so that the 87Rb atoms' resonant absorption can be monitored by means of phase-sensitive detection. The detector's output yields a correction voltage, proportional to the derivative of the resonance line shape, which is used to adjust VCOCXO and lock it to the transition frequency between two hyperfine states of 87Rb. As illustrated in Figure 2, the Physics body of the clock consists of a 87Rb discharge lamp, a 85Rb -vapor filter cell, and a resonance cell containing 87Rb vapor along with a buffer gas. Each element plays a role in generating the atoms' response to the microwaves. For now, it suffices to note that the atoms' resonant absorption of microwave radiation is manifested by a decrease in the transmitted light intensity. The resonance cell is located inside a microwave cavity, which in turn resides inside a solenoid(C-field coil). The solenoid's magnetic field provides a quantization axis for the atoms, isolating the 0-0 transition. Moreover, since the 0-0 resonance has a second-order dependence on magnetic-field strength, the solenoid provides a convenient means of making slight adjustments to the transition frequency between two hyperfine states and thereby the clock's frequency.

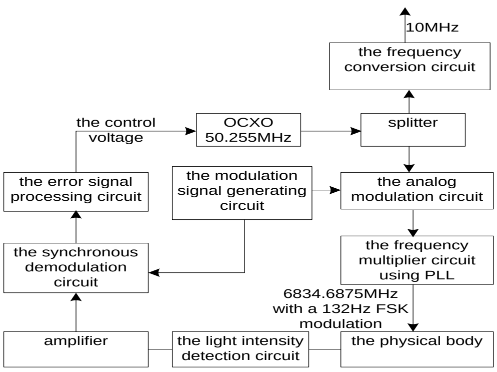

Figure 1. The Functional Block Diagram of the Rubidium Atomic Clock Designed

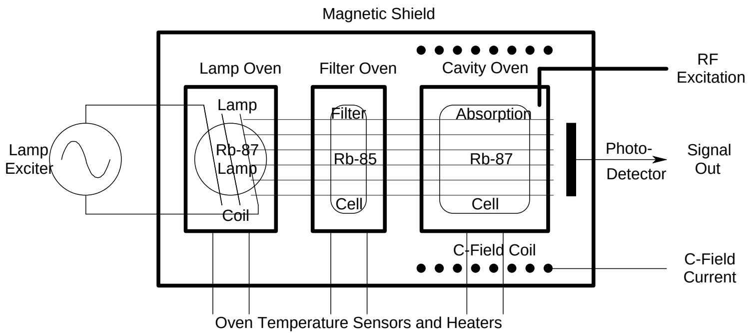

Figure 2. The Physics Body of the Rubidium Atomic Clock Designed

The major reasons that temperature influences rubidium atomic clock's output frequency are as follows: First of all, the collision rules of rubidium atomic in the absorption cell vary as temperature varies, resulting in buffer gas frequency shift [5-7]; Secondly, the central frequency of the resonant cavity is a function of temperature and when temperature varies, the cavity's central frequency varies. As a result of cavity's pulling effect, the central frequency of atomic frequency spectrum varies, resulting in cavity pulling frequency shift [8-10]; Thirdly, the variation in temperature may lead to the frequency spectrum of the light variation, resulting in optical frequency shift [11-12]; The fourth factor is that the variation in temperature leads to variation in rubidium atomic density in the absorption cell, also resulting in frequency shift [13]; Lastly, the variation in temperature may influence the power of microwave circuit's output, resulting in microwave power frequency shift. The frequency shifts mentioned above are difficult to be distinguished by experiment methods. They play combined effects on the performance of the rubidium clock frequency-temperature characteristic. It is clear that the frequency-temperature characteristics are formed by many factors. Among these factors, some are positive to total frequency-temperature characteristic and others are negative. Therefore, reasonable optimal design of all parts, such as using an optimal ratio of the buffer gas with the rubidium gas and using a proper light density in the absorption cell, may reduce the whole clock's frequency-temperature characteristic[1,2]. However, this method requires lots of theoretical calculation and high level of manufacturing technique.

The direct digital frequency synthesis (DDS) technology is one of the widely used frequency synthesis technologies, which has the features of quick conversion and high resolution. DDS is a technique using digital data processing blocks as a means to generate a frequency and phase tunable output signal referenced to a fixed-frequency precision clock source[14-17]. Making use of DDS's high resolution characteristics, one can compensate an atomic clock temperature-frequency characteristic by adding a DDS on the atomic clock's output circuit.First, test the parameter of the frequency-temperature characteristics. Then, design a temperature measuring circuit for testing the ambient temperature. In accordance with tested results of the parameters and the ambient temperature, the controller (usually is a single chip microcomputer) calculates the frequency variation of the atomic clock's output caused by variation in ambient temperature. Afterwards, the frequency control word of the DDS will be changed and a compensated output will be obtained.

Suppose that at t_1 ^{0}C the atomic clock's output frequency is f_0. At t_2 ^{0}C, influenced by the atomic frequency-temperature characteristics, the atomic clock's output frequency is f_2, then f_1 and f_2 have the following relation

$$f_2 - f_1 = K_T(t_2 - t_1) \tag{1}$$

Suppose that at t_1 ^{0}C,the output frequency of the DDS is f_{t1}, and the frequency control word of the DDS is FTW ,with N bits, then, we can obtain that

$$f_{t1} = \frac{FTW}{2^N} f_1 \tag{2}$$

At t_2 ^{0}C, adjusting the frequency control word may maintain the output frequency unchanged when temperature varies. Suppose the control word adjusted is FTW^1， then

$$f_{t1} = \frac{FTW^1}{2^N} f_2 \tag{3}$$

f_{t1} is known and f_2 can be obtained by formula 1. Then, the result of the FTW^1 can be obtained by the formula 3，in other words, we can make the DDS's output unchanged when temperature changes.

The current design scheme of the atomic clock's frequency synthesizer provides a convenience to adjust the frequency synthesizer's parameters. As the transition frequency of the atomic is usually a decimal frequency and the DDS has advantage in generating decimal frequencies, the DDS technology is widely used in the atomic clock [2 ,7]. The adjustment of the frequency synthesizer parameters can be realized by changing the DDS's output frequency and this adjustment has advantages such as high resolution and limited interference.If the DDS's frequency control word is 48 bits and the reference clock's frequency is 100MHz, the resolution of the DDS's output frequency can reach 3.55×10^{-7}Hz when adjusted and when using this DDS to produce a nominal value 10MHz, the resolution 3.55×10^{-14} can be reached and can be used to adjust the value of the output frequency and the atomic clock frequency-temperature characteristics may be improved. If the resolution 3.55×10^{-14} is used to adjust the DDS's output, the atomic clock frequency-temperature characteristics may be remarkably improved.

The second scheme to improve the atomic clock's temperature-frequency characteristics is closely connected with the atomic clock's locking principle. The atomic clock is a frequency locking system and the local oscillator's frequency will be locked to the transition frequency of the atomic. The atomic clock mainly comprises of four parts and each part is subject to the influence of temperature. As the atomic clock is a loop-locked system, all kinds of errors can transmit within the system, the influences which equal to errors can transmit in the system, then, the influences can be equalized as the errors of the transition frequency of the atomic.

In realization, measure the whole clock's frequency-temperature characteristic firstly and calculate the transition frequency secondly. When the fluctuation of the temperature is bigger than the threshold, adjust the frequency synthesis's parameter thirdly and the clock's frequency-temperature characteristic compensation may come true. If the atomic clock's output frequency is f_1 at t_1 ^{0}C，the transition frequency of the atomic is $f_{atomic1}$，the frequency synthesizer's parameter is K， then

$$Kf_1 = f_{atomic1} \tag{4}$$

At t_2 ^{0}C，suppose the atomic clock's output frequency is f_2, then, by $Kf_2 = f_{atomic2}$, a new transition frequency of the atomic $f_{atomic2}$ would be obtained, obviously,

$$f_{atomic2} \neq f_{atomic1} \tag{5}$$

This is resulted from the whole clock's frequency-temperature characteristic. Suppose that

$$K^1 f_1 = f_{atomic2} \tag{6}$$

Then , by the formula 6, K^1 can be obtained. When temperature changes to t_2 ^{0}C, adjusting the frequency synthesizer's parameter to K^1, the compensation can be realized and the whole clock's frequency-temperature characteristic will be improved.

Despite of the DDS's high resolution characteristics, a certain amount of noise and interference will be introduced in the above process, which is due to amplitude quantitative errors, phase quantitative errors, errors caused by the limited bit length of the memorizer, DAC nonlinear error, the noise and interference produced by the circuit *etc*.

It is obvious that the second scheme has a higher resolution than the first one. However, it does not mean that a higher resolution is equal to a high-performance frequency-temperature characteristic. Not only the high resolution but also the adjustment process with low noise and interference quality are met, then a high-performance frequency-temperature characteristic can be gotten. Improvement of rubidium clock's frequency-temperature characteristic by compensation technical has two characteristics, one is that the magnitude of compensation is little; the other one is that the introduced noise and interference is ignorable. The reason is that the frequency adjustment can be realized in a step-by-step way and the time interval between two steps can be longer than the modulation signal's period.

The second scheme has theoretical advantage compared with the first one. As the DDS is widely used in the current atomic clock, almost no hardware needs to be added if the second scheme is used. As it has been argued, frequency conversion based on DDS may produce some factors which can affect frequency stability [8,9,10]. In the first scheme, the DDS's output becomes the atomic clock's output. If the DDS's output is used as the atomic clock's output, all of the performance parameters must be satisfied to the performance parameters of the atomic clock, which leads to a very high demand on DDS's performance (such as precision, stability , phase noise, harmonic wave, noise wave *etc*). In the second scheme, as the atomic clock's physical body is like a band-pass filter with a high Q value, the noise and interference of the DDS's output may be greatly reduced and the demand on the DDS's performance may be not so much. In next section, the paper will make some experiments to illustrate this.

3. Experimental

It needs to redesign the internal circuit of the atomic clock when the scheme 2 is used. At present, only the scheme 1 has been researched by experiment. The experimental scheme is shown as Figure 3.

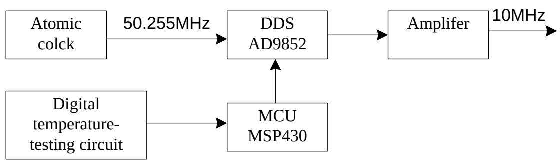

Figure 3. The Block Diagram of the Experiment

In the experiment, the rubidium clock we made was selected as the experimental object. First of all, the frequency-temperature characteristic of the clock was measured and the results is shown in Table 1, then a DDS circuit whose reference signal was the output of the rubidium clock, was used to give a new output. The DDS circuit was controlled by a MCU and the MCU would adjust the output of the DDS by adjusting the frequency control word. And the frequency control word was adjusted according to the algorithm and the original frequency-temperature characteristic mentioned above. The aims of the experiments were as follows: the first one was to test the validity of the method and the second one was to examine whether the output of the DDS could meet the demand for the current atomic clock.

The major hardware were the temperature measurement module and the DDS module when using the scheme 1.The design and performances of the temperature measurement module were the keys to realize high compensation precision and the design method put forward in the reference 6, which had many advantages such as high resolution, digital and easy debugging, was used in the experiment. The temperature measurement module was designed by calculating the time lengths of the two charge(from zero to a trigger level set by the circuit and the software) that one time length was the charge time of a RC active circuit, which was mainly comprised of a reference resistor with high precision and a high stable capacitance . The RC active circuit was charged by a constant voltage source. In the other RC active circuit the reference resistor was replaced by the PT1000 which had an almost linear relationship with the temperature. The resistance of the PT1000 could be calculated according to the value of reference resistance and the temperature could be calculated further more according to the linear relationship between the temperature and the resistance value of the PT1000. In theory, the designed temperature-measurement module was immune to noise of the power supply and variation of the temperature. The major factors affecting the measurement precision were the triggering error and the ±1 counting error when the module worked. The results of the experiment showed that the resolution of the circuit was as high as 0.01^0C.

Two methods are often used when calculating the temperature according to the PT1000's resistance value. One is formula fitting calculation method and the other one is table checking method. The low precision is the drawback if the first order linear fitting formula is used for calculation.In the table checking method, the high demand for resolution and measurement range needs large memory. Restricted by the controller's performance, all these methods are not suitable. This paper has designed a solution method by combining table checking method with linear fitting method. In the range from -20^0C to 60^0C, the resistance value of the PT1000 and its corresponding compensation data is stored at an interval of 10^0C. This remarkably reduces the amount of data which needs to be stored. Linear fitting method is adopted to obtain high resolution temperature. Suppose at t^0C （t is an integer in the range from -20 to 60） ,the corresponding PT1000's resistance value is a_1 , at $(t+10)^0C$, the corresponding PT1000's resistance value is a_2. To simplify compensation process, only when temperature variation exceeds 0.1^0C, re-compensate is done .Otherwise previous compensation value is maintained. Frequency adjustment is performed step by step at 5×10^{-13}, at an internal of 1ms between the two steps, with one adjustment completed within 1s. The purpose of this is to improve the stability of atomic clock's output and to increase compensation speed[18].The DDS module was mainly composed of a MCU, a DDS IC chip, a 10MHz filter and a 10MHz amplifier.

4. Results and Analysis

When the method mentioned is used for compensating the rubidium clock's frequency-temperature characteristic, the frequency measurement system with high accuracy should be built first. We design the frequency measurement system based on the measurement of the period of the difference frequency signal, whose functional block diagram is shown in Figure 4. The basic principle is to measure the period of the difference frequency signal by counter, which is generated from reference signal and measured signal by the low noise mixer. Measuring frequency by the beat method of frequency measurement brings about high resolution. Suppose the value of the measured frequency f_x and the reference frequency f_0 is 10MHz, while the difference frequency Δf is 1Hz ,which means the period is 1s. If the time mark of the counter is 0.1us, the relative error of periodic measurement which caused by ±1 counter error is:

$$\frac{\Delta\tau}{\tau}=\frac{\pm 0.1\mu s}{1s}=\pm1\times10^{-7} \quad (7)$$

The total resolution is:

$$\frac{\Delta f_x}{f_x} = \frac{\Delta \tau}{f_o \tau^2} = \frac{1\times10^{-7}}{10\times10^6\times1} = 1\times10^{-14}/s \qquad (8)$$

From the above analysis, using the beat method of frequency measurement for measuring frequency stability brings high resolution. The measurement of the difference frequency signal is accomplished by the measure, control and data center ,then the measured frequency values is calculated according to the period of difference frequency signal. In real work, the OSA 8607 ultra high temperature crystal oscillator is selected as the reference source, HP8607 as the frequency synthesizer and HP53131 complete the measurement of the period ,then manual recording of experimental data is achieved.

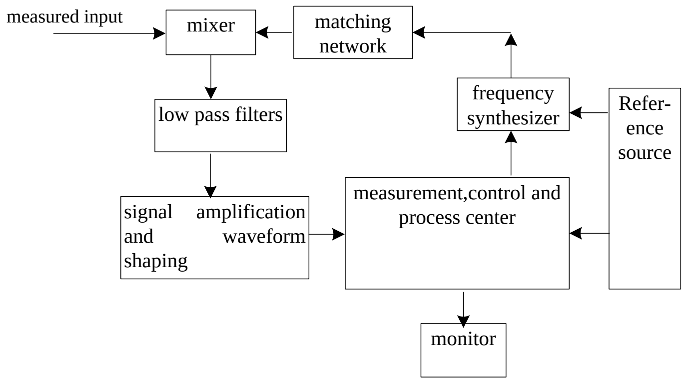

Figure 4. Functional Block Diagram of the Measurment System with High Accuracy

Put the atomic clock in the control cabinet and set a point at an interval of 10℃ from -20℃ to 60℃ that the measured frequency data is measured and stored, which is shown in Table 1. This remarkably shows that no matter what the measuring point is, measurement results fluctuate around 8×10^{-11}Hz indicating that the measurement results fluctuate at the order of 8×10^{-12}. This may be caused by measured atomic clock's frequency stability and some unstable factors of the frequency measurement system which are mainly composed of cesium clock instability, instability introduced by related circuit (including frequency synthesizer, mixer, *etc*.) and the resolution of the instrument . The second instability of the measured atomic clock is about 5×10^{-12}, while the resolution of the instrument error which due to the high accuracy difference frequency cycle can be ignored, so does the second stability of reference source ,which is 10^{-13}.The total instability of the measurement results is about 8×10^{-12}, which is believed to be the reason to cause the instability of the reference source and the instability of measurement system’s circuit.

Table 1. The Output Frequency before Compensation

Temperature （^{0}C）	Output frequency before compensation(MHz,1s measuring gate, an average of 10 measurements ）	Temperature （^{0}C）	Output frequency before compensation(MHz,1s measuring gate, an average of 10 measurements ）
-20	$9.99999998648\pm3\times10^{-11}$	30	$9.99999998691\pm4\times10^{-11}$
-10	$9.99999998654\pm4\times10^{-11}$	40	$9.99999998705\pm3\times10^{-11}$
0	$9.99999998673\pm4\times10^{-11}$	50	$9.99999998713\pm4\times10^{-11}$
10	$9.99999998685\pm3\times10^{-11}$	60	$9.99999998717\pm3\times10^{-11}$
20	$9.99999998688\pm3\times10^{-11}$		

Plot temperature frequency curve according to the measurement results, as is shown in Figure 5. In order to clarify the relationship of temperature and frequency variation, the atomic clock's frequency at -20 °Cis recognized as the nominal frequency. Frequency-temperature characteristics of the clock are linear with frequency before compensation, which is obviously observed from Figure 5. The least square method can be used to obtain the frequency-temperature coefficient which is about 8.75×10^{-12}/°C. Through the analysis of the data in Table 1, it is not difficult to find that the frequency-temperature characteristic of the measured atomic clock also has non-linear characteristics. The data in Figure 6 is obtained from Table 1 by getting the deviation between the frequency offset and the fitting line, which gives a visual representation of the nonlinear relationship of the frequency-temperature characteristic.

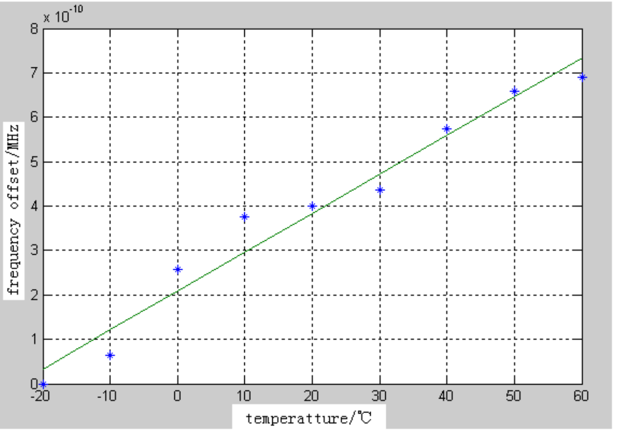

Figure 5. Frequency-Temperature Characteristic Curve Before Compensation

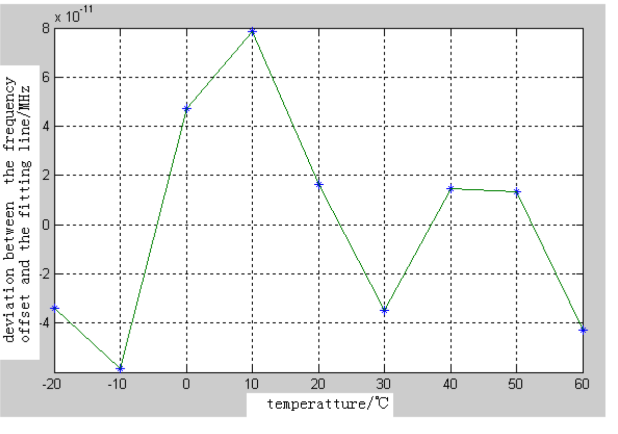

Figure 6. Nonlinear of the Frequency-Temperature Characteristic before Compensation

The frequency-temperature characteristic of the clock is compensated by the means of piecewise compensation introduced in this paper. The results after compensation are shown in Table 2 which reveals that when the outside temperature varies from -20 ℃ to 60 ℃, the frequency offset isn't more than 1.6×10^{-10}MHz. The frequency-temperature curve after compensation is shown in Figure 7. Table 2 shows that the compensation method has very high precision at the endpoints. Figure 7 shows that the frequency-temperature characteristic curve after compensation has obvious non-linear relationship.

Experimental results show that the compensation method can compensate the affect of the nonlinear to a certain extent.

The frequency stability of the experiment clock was measured both with and without the thermal compensation circuit and the results are given in Figure 8. The stability curve with triangular symbol on is the stability curve with the compensation and the curve with square symbol on is the stability without the compensation. They are almost samely and this character is consistent with the earlier analysis . The stability , phase noise, harmonic wave, noise wave of the 10MHz signal outputted by the DDS are all perfect and meet the need of the clock well the phase Noise of the 10MHz signal outputted by the DDS is shown in figure 9. The signal outputted by the DDS is adjustable and a very high accuracy can be gotten[10]. In conclusion, based on the compensation method mentioned above, the atomic clock's frequency-temperature characteristic can be improved and other performances of the atomic clock are not impaired if the circuit design is reasonable.

Table 2. The Output Frequency after Compensation

Temperature (°C)	Output frequency after compensation(MHz,1s measuring gate, an average of 10 measurements)	Temperature (°C)	Output frequency after compensation(MHz,1s measuring gate, an average of 10 measurements)
-20	$10.00000000004\pm3\times10^{-11}$	25	$10.00000000001\pm6\times10^{-11}$
-15	$10.00000000017\pm3\times10^{-11}$	30	$10.00000000007\pm4\times10^{-11}$
-10	$10.00000000008\pm4\times10^{-11}$	35	$10.00000000017\pm4\times10^{-11}$
-5	$10.00000000011\pm4\times10^{-11}$	40	$10.00000000003\pm3\times10^{-11}$
0	$10.00000000003\pm3\times10^{-11}$	45	$10.00000000015\pm3\times10^{-11}$
5	$10.00000000008\pm3\times10^{-11}$	50	$10.00000000005\pm4\times10^{-11}$
10	$10.00000000004\pm4\times10^{-11}$	55	$10.00000000006\pm4\times10^{-11}$
15	$10.00000000013\pm4\times10^{-11}$	60	$10.00000000008\pm4\times10^{-11}$
20	$10.00000000001\pm6\times10^{-11}$	65	$10.00000000014\pm4\times10^{-11}$

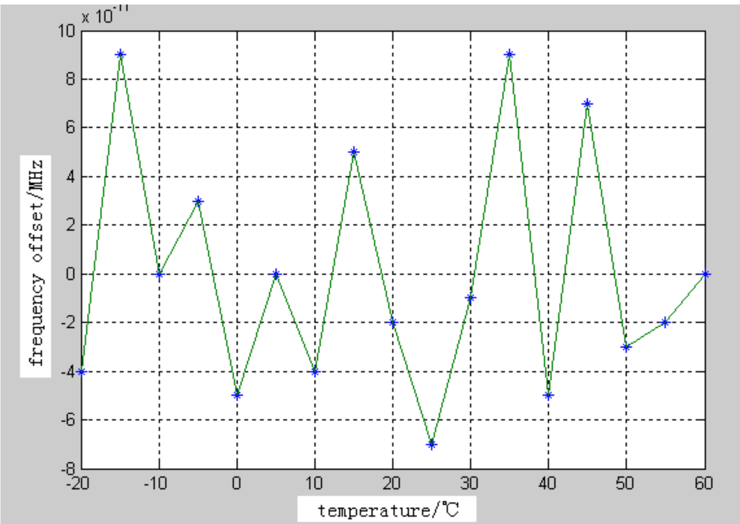

Figure 7. Frequency-Temperature Characteristic Curve after Compensation

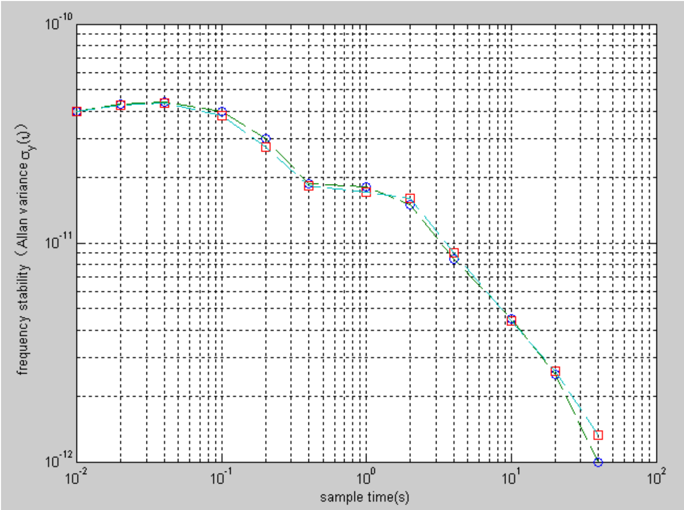

Figure 8. Test Results of the Frequency Stability Both with and Without the Compensation.

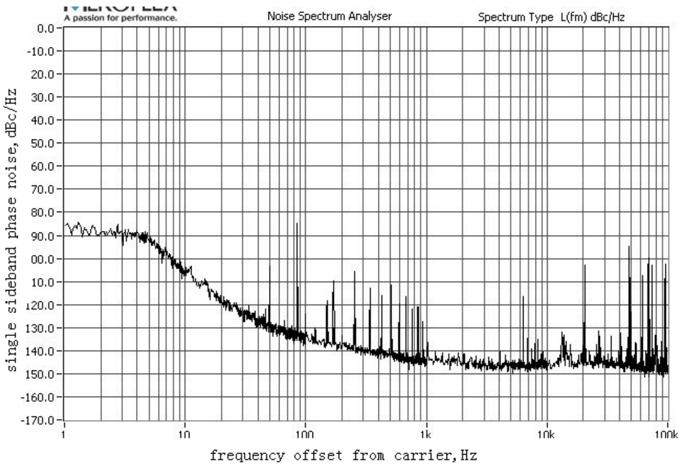

Figure 9. Phase Noise of the Dds Output

Summaries

The method proposed in this paper to improve rubidium clock frequency-temperature characteristic is featured for easy realization and easy adjustment, compared with traditional methods. The further studies of this paper include the design and realization of a temperature measurement circuit with a much higher measuring accuracy than 0.01^0C and a wider measurement range than that from -20^0C to 60^0C, the optimization of the signal processing method and make further experiment studies to the satellite-borne rubidium atomic clock based on the scheme 2. As the method proposed in this paper only can reduce the regular errors in atomic clock's frequency-temperature characteristic and is not effective to random errors, researches to reduce random errors in atomic clock's frequency-temperature relationship are in need.

Acknowledgement

This work was supported by the foundations of the Central Universities of China for basic scientific research and professional work under contract (CHD201JC080,CHD2011TD012) ,the Industrial research project of Shaanxi Province under contract (2011K06-32),the Natural Science Foundations of China (60772135,10978017) and the Postdoctoral Science Foundation of China(2013M530411)

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